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PREPARED FOR

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER
MARSHALL SPACE FLIGHT CENTER, ALABAMA 35812

CONTRACT NAS 8-36418

PREPARED BY:

Rockwell International

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Hugh M. Campbell
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SPACE STATION PROPULSION TECHNOLOGY

FIRST ANNUAL PROGRESS REPORT

24 MAY 1985 - 23 MAY 1986

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0737p-105-2

INTRODUCTION

This annual progress report for the period 24 May 1985 through 23 May 1986 describes the progress on the Space Station Propulsion Technology Program, NAS8-36418 during the first contract year. The objectives of this program are to provide a demonstration of hydrogen/oxygen propulsion technology readiness for the IOC space station application, specifically gaseous hydrogen/oxygen and warm hydrogen thruster concepts, and to establish a means for evolving from the IOC SSPS to that required to support and interface with advanced station functions. These objectives are met by analytical studies and by furnishing to MSFC for testing a propulsion test bed.

The program is organized in six tasks. In Task I, Candidate IOC SSPS Concept Definition, a range of design concepts for the IOC SSPS were synthesized and evaluated. The most attractive candidates will be carried into a more detailed conceptual design. In Task II, SSPS Test Bed Design and Fabrication, the propulsion test bed is designed, fabricated and delivered to MSFC with associated test plans and documentation. A contract change to modify an existing O_2/H_2 thruster for test bed operation at a mixture ratio of 8 has been added to this effort. In Task III, Advanced SSPS Concept Definition, evolutionary growth concepts will be synthesized and evaluated.

Under Tasks IV, V, and VI, Rocketdyne provides ongoing support to the test program carried out by MSFC and conducts configuration updates as needed to demonstrate evolutionary growth concepts.

During the first contract year, the evaluation of concepts was completed and presented in a concept evaluation briefing. The accumulator module of the test bed was completed and, with the microprocessor controller, delivered to NASA-MSFC. An oxygen/hydrogen thruster was modified for use with the test bed and successfully tested at mixture ratios from 4:1 to 8:1.

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A hiatus in contract funding occured in the period February to June 1986. During this period, results of studies being conducted under Space Station Phase B showed that use of waste water electrolysis to generate propellant oxygen and hydrogen had significant advantages over the originally planned supercritical transportation and storage approach. Therefore, effort on this contract during the next year will be directeed toward proving out the use of electrolysis using the accumulator module and water electrolysis unit modules supplied from other efforts.

OVERALL PROGRESS

During the first contract year overall progress was outstanding. The test bed and controller were delivered in December (Figure 1) and a significant demonstration of O_2/H_2 thruster readiness was conducted in April. The Task I concept study was completed in November.

TASK I CONCEPT DEFINITION

As illustrated in Figure 2, this study assumed the reference power tower space station configuration and the reference four location propulsion system. The electrical power system was assumed to incorporate eight planar silicon photovoltaic arrays. A 250-nautical mile station assembly and resupply altitude was used with a reference 2σ density atmosphere.

The SSPS functions included velocity corrections and attitude control. The velocity corrections requirements consisted of atmospheric drag makeup (reboost), debris avoidance, and reserves. The attitude control requirements included reboost attitude control, provided torques exceeding Control Moment Gyros (CMG) capacity, CMG backup, and CMG desaturation.

As shown in Figure 2, the SSPS requirements evaluated considered the station architecture, propulsion system performance, SSPS operations, interfaces, and SSPS evolution and opportunity. Each of the velocity correction and attitude control requirements were evaluated with the determination of the impact on the SSPS, the design basis, and the design selection sensitivity to baseline change.

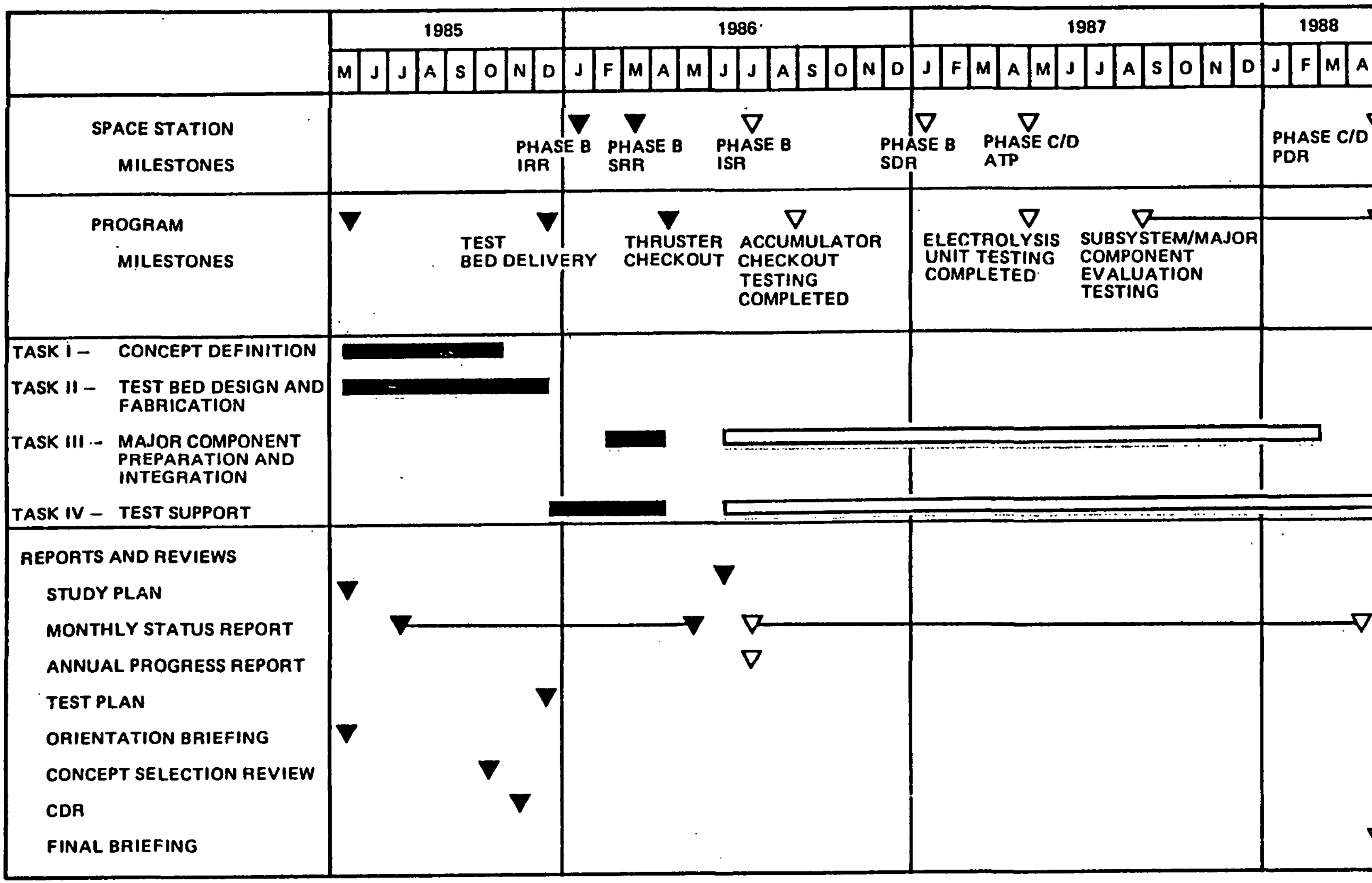

Figure 1. Program Schedule
(Revised 24 June 1986)

SCOPE OF REQUIREMENTS CONSIDERED

- ARCHITECTURE
  - MASS
  - SIZE
  - SHAPE
- PERFORMANCE
  - ATTITUDE CONTROL
  - VELOCITY CONTROL
- OPERATIONS
  - SAFETY
  - MAINTENANCE
  - CUSTOMER ACCOMMODATIONS
  - CREW ACTIVITIES
- SYSTEM INTERFACE
  - GNC
  - EC/LSS
  - OTHERS
- EVOLUTION AND OPPORTUNITY
  - CUSTOMER NEEDS
  - ADDITIONAL FACILITIES
  - UTILITY SERVICE ($O_2/H_2/H_2O$)

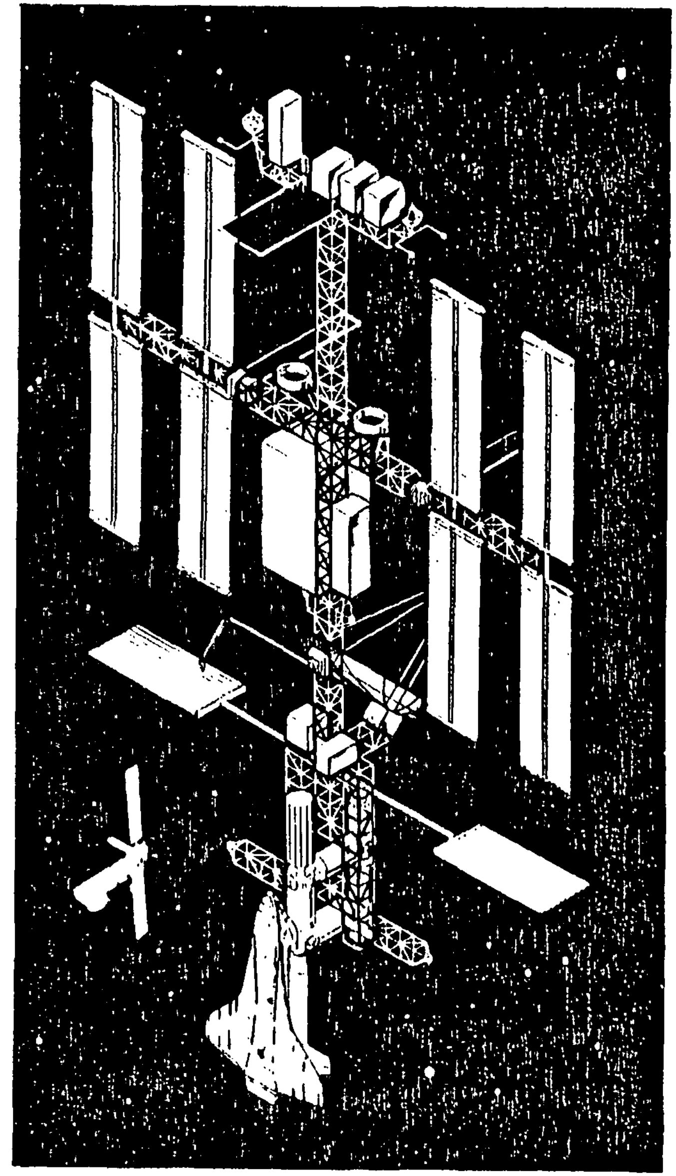

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Figure 2

The station safety requirements specify a fail operate/fail safe/restorable system with designed-in safety. The latter would include damage containment. The customer accommodation requires a micro-gravity ($<10^{-5}$g) and contamination-limited environment. The processing and operations requirements include the need to access, service, and maintain the SSPS and the SSPS is to be launched in the Space Transportation System (STS). System maintenance and servicing requirements consist of: (1) easy replacement at lowest Orbital Replacement Unit (ORU); (2) condition-monitoring fault detection; and (3) propellant resupply servicing.

For this study task, two different impulse requirements were evaluated. These are shown in Table 1 and the proposed reboost committee values (dated July 8, 1985). The total 90-day impulse values were similar for the two impulse requirements. For the reference impulse, the reboost impulse is approximately one-third of the total impulse (2/3 contingency). In the reboost committee impulse, the reboost impulse is approximately 75-percent of the total impulse.

During the conduct of this task, the dual keel station configuration (Figure 3) was just introduced and the changes in impulse values were not defined.

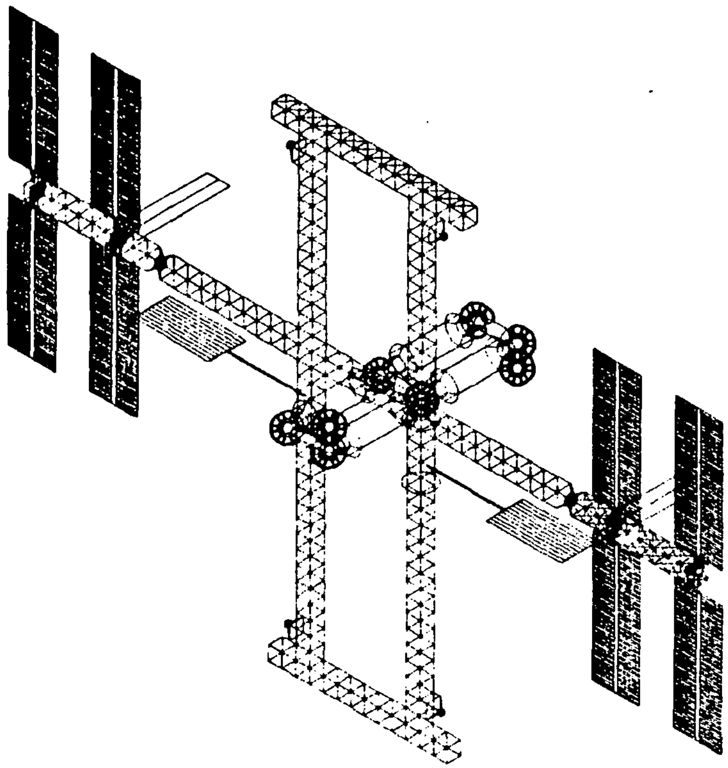
System Evaluation

The system evaluation of the oxygen/hydrogen-based propellant SSPS involved: (1) the synthesization of potential candidate systems which were reduced in number by conducting a preliminary screening; (2) the development of a selection methodology with the establishment of selection criteria and their relative importance; and (3) the evaluation of the candidate system to define comparative data for each selection criteria.

Table 1. IOC Impulse Design Requirements
(2 sigma atmosphere)

	90-Day Impulse, lbf-sec			
	Reference	10-Year Average	Proposed Reboost Committee (8 July 1985)	10-Year Average
• Reboost and Other Resupplied Propellants				
• Reboost (Drag Makeup)	483,000	224,000	854,000	400,000
• Orbit Makeup Attitude Control	--	(RJ)	221,000	100,000
• Momentum Mangement	--		57,000	
• Transients				150,000
• Orbiter berthing	26,000	26,000	26,000	
• Other	--	(Thruster)	66,000	
Subtotal (Resupplied Propellants)	509,000	250,000	1,224,000	650,000
• Contingency				
• Collision Avoidance (ΔV = 5 fps)	61,500		70,000	
• Altitude Transfer (20 n mi.)	831,000		--	
• Attitude Control Backup - GMGs	147,000		269,000	
• CMG Repair	--		11,000	
• Reserve (10% of Reboost)	--		85,000	
Subtotal (Stored Propellants)	1,039,500		435,000	
• Total Impulse	1,548,500		1,659,000	

DUAL KEEL CONFIGURATION



POSSIBLE IMPACT ON SELECTION

- ACS IMPULSE
  - GRAVITY GRADIENT STABILIZATION
  - ORBITER BERTHING
  - RE-BOOST REQUIREMENTS
- ACS TORQUE LEVEL
- SINGLE POINT REBOOST
- LINE LENGTHS
- NEED FOR ACTIVE CONFIGURATION CONTROL

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Figure 3

System Synthesis. The major emphasis in synthesizing candidate O_2 and H_2 based propulsion systems to be evaluated was to strive for system simplicity. Candidate systems incorporating pumps, turbines, or gas generators were eliminated due to their increased system complexity. To maintain the propellant storage volume and meet minimum required thruster inlet temperatures (200R for H_2 and 400R for O_2), propellant thermal conditioning is required. Also one attractive approach to propellant tank pressurization is through heat addition. Since this energy required for tank pressurization and propellant thermal conditioning could utilize electrical power, the energy rate should be minimized. Therefore, to minimize energy requirements, accumulators are required to decouple the tank pressurization and thermal conditioning from the thruster operation and reduce the rate of energy consumption.

An initial screening of the candidate systems assessed system complexity, system volume, and energy requirements and resulted in the eight candidate systems presented in Table 2. These include O_2/H_2 and warm H_2 systems without and with H_2 resistojets and integrated with the ECLSS, a O_2/H_2 system with dedicated water electrolysis, and a combined warm H_2 Attitude Control System (ACS) with a O_2/H_2 drag makeup system. Sample schematics of these candidate systems are presented in Figures 4 and 5.

The propellant, their origin, type of thruster, and whether the candidate system would be used for drag makeup (low or high thrust) and/or attitude control (high thrust) are summarized pictorially in Figure 6 for all candidate systems.

Evaluation. The eight candidate SSPS were evaluated in sufficient depth for each evaluation criterion to discriminate between the different systems. Detailed system schematics were prepared defining the component arrangement, component type, and redundancy. The overall and resupply system weight, volume, and energy requirements were determined. The assumptions and groundrules used in this evaluation are shown in Table 3.

Table 2. IOC SSPS Candidate Systems

1	Oxygen/Hydrogen
2	Warm Hydrogen
3	Oxygen/Hydrogen + Hydrogen Resistojet
4	Warm Hydrogen + Hydrogen Resistojet
5	Oxygen/Hydrogen from Water Electrolysis
6	Oxygen/Hydrogen Integrated with ECLSS
	• with CO_2 Resistojets
	• with CH_4 Resistojets
7	Warm Hydrogen Integrated with ECLSS
	• with CO_2 Resistojets
	• with CH_4 Resistojets
8	Combined Alternate
	• Warm Hydrogen ACS with Oxygen/Hydrogen Drag Makeup

SSPS CANDIDATES

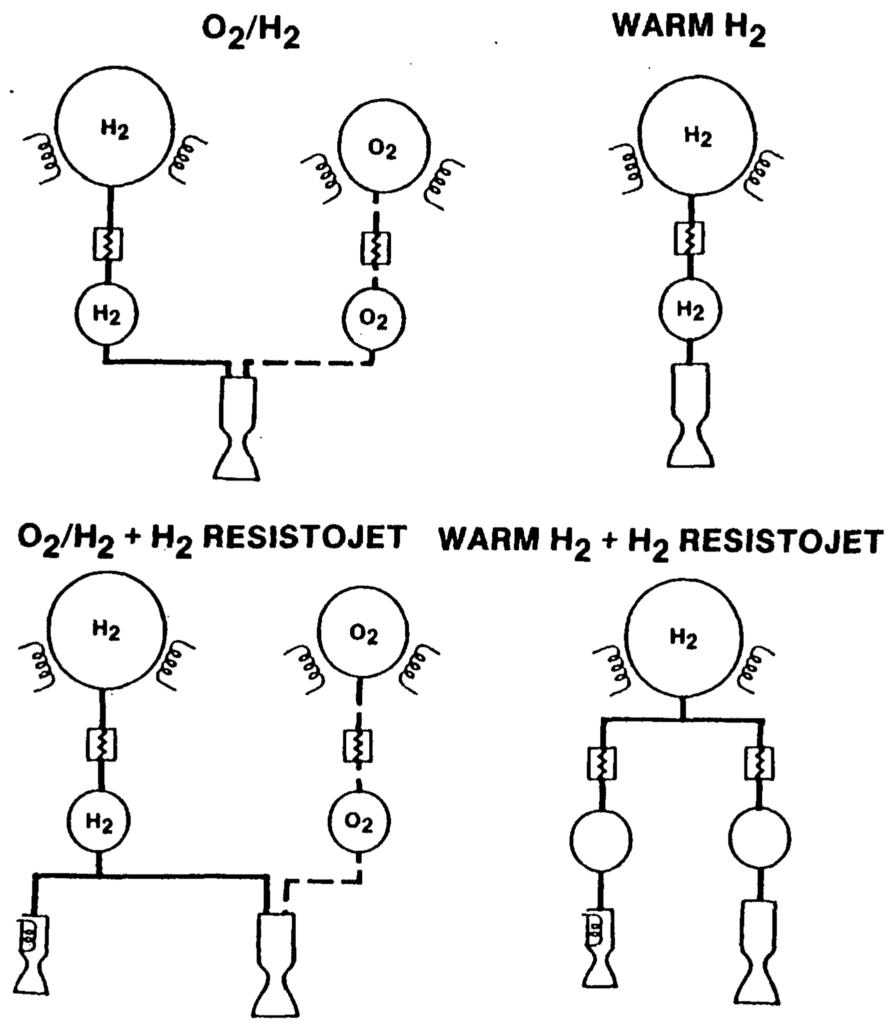

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Figure 4

SSPS CANDIDATES

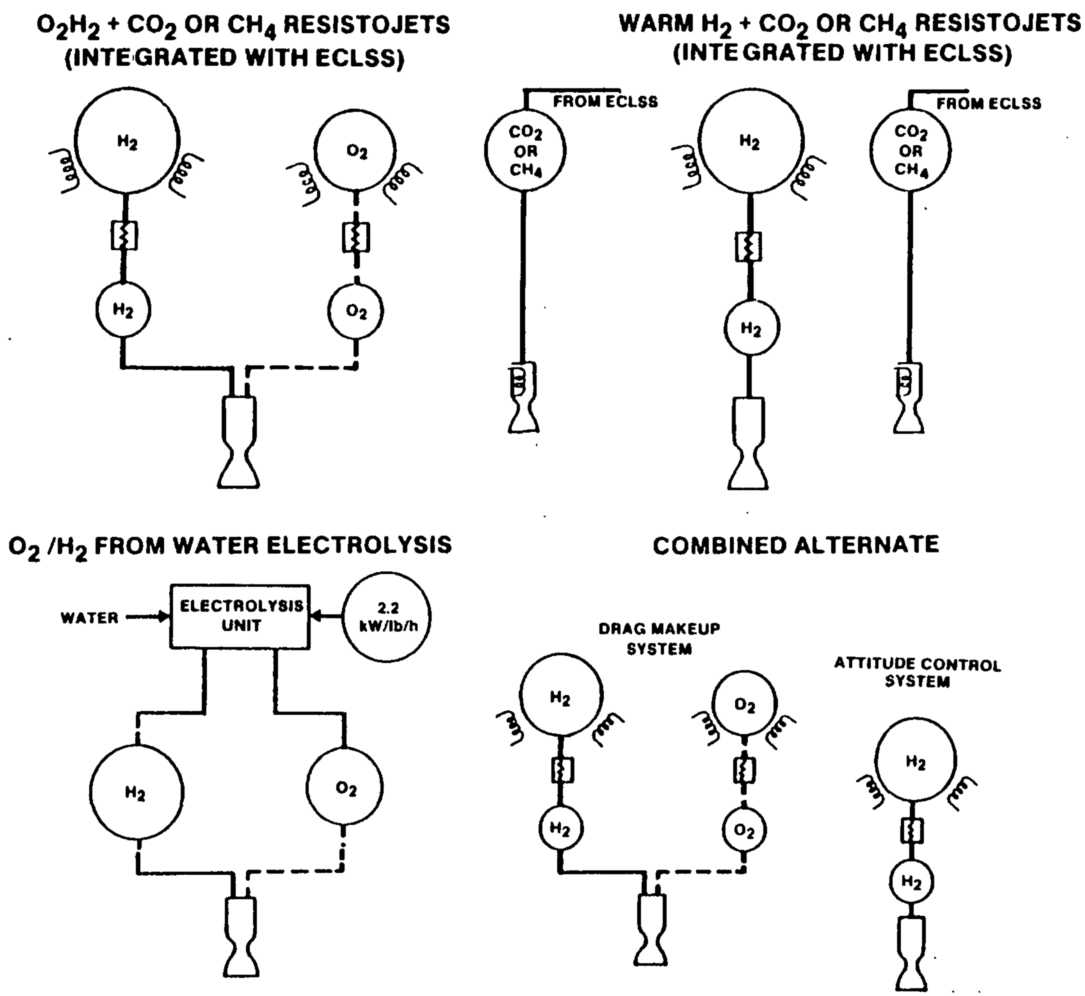

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Figure 5

SSPS CANDIDATE CONCEPTS

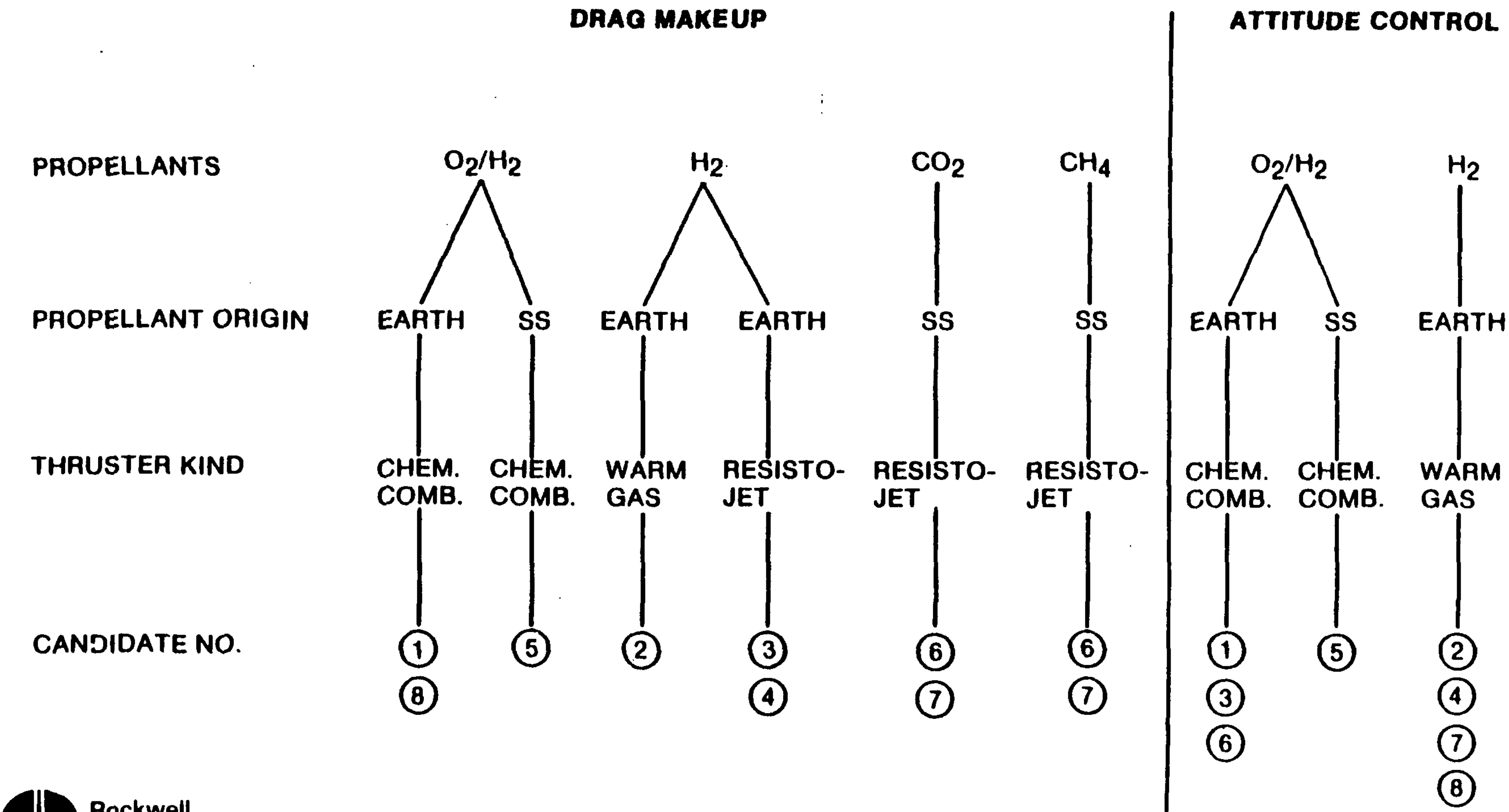

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Figure 6

Table 3. Assumptions/Ground Rules

- Supercritical Storage for IOC Station
- Centralized Propellant Storage and Thermal Conditioning with Modular Accumulators
- Thermal Conditioning of Propellant by Electrical Heater with Larger Thermal Inertia
- Accumulators Operate in Blowdown Mode (no heat added during blowdown)
- Nominal Mixture Ratio of 4:1 ± 1 for Oxygen/Hydrogen Bipropellant
- System Supplies Propellant to Four 25-lbf Thrusters, Possibly Also Resistojets
- Long-Duration Hardware Soak Temperature Will Reach ~600 R
- Minimum Thruster Inlet Temperatures: 200 R (hydrogen), 400 R (oxygen)
- Maximum Tank Diameter is 9 Feet (cube dimension)
- Specific Impulse Values
    - Oxygen/Hydrogen 440
    - Warm Hydrogen 270
    - Hydrogen Resistojet 500
    - CO_2 130
    - CH_4 160
- Maximum Available Power 10% of Total Station Power

Selection Methodology. To ensure an objective candidate selection, a structured evaluation and selection methodology was used. The overall selection process is schematically illustrated in Figure 7 and involves the generation and compilation of data pertinent to specific evaluation criteria which are quantified to a numerical rating. The steps involved in this procedure are presented in Table 4.

As shown in Table 4, the selection criteria to be used in the selection were first developed. This was accomplished through a review of the SSPS requirements identifying critical areas of concern and through interaction with NASA-MSFC personnel. Table 5 presents the seven selection criteria defined for the SSPS and the specific items influencing each criterion (subcriteria). The criteria included reliability and safety, contamination potential, technical risk, IOC and Life Cycle Cost (LCC), growth potential, operational utility, and potential Space Station Program Element (SSPE) interaction.

Relative weighting factors for each criteria were determined by establishing the relative importance of each factors. A total of nineteen technical experts were surveyed. Through the use of Rocketdyne's Analytical Hierarchy Process (AHP) computer code, the survey results were quantified as shown in Figure 8. Reliability and safety were the most important criterion followed by contamination and technical risk. IOC and life cycle cost was the fourth highest criteria. The SSPE integration criteria was the least important criteria.

Next, a preliminary point design of each candidate system was established and data generated to enable a numerical rating for each criterion. Each criterion ranking is multiplied by the corresponding weighting factor to obtain a weighted rating. This is performed for each criterion for each candidate system. The sum of the weighted ratings for a candidate system is the overall rating. The candidate systems are then ranked according to the numerical value of the overall rating. The sensitivity of the weighting

CONCEPT SELECTION PROCESS

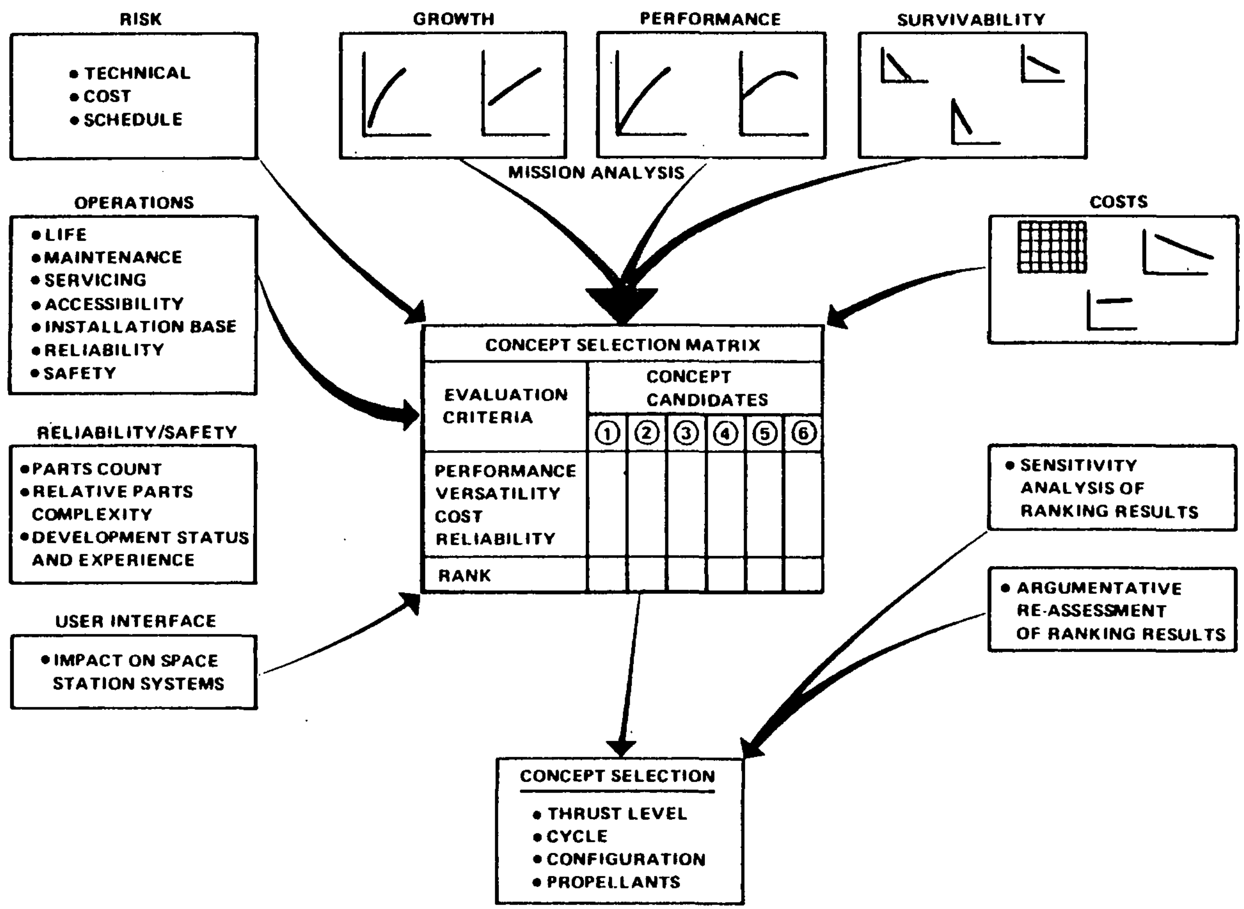

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Figure 7

Table 4. Concept Selection Approach

- Develop Selection Criteria
- Establish Weighting Factors for Selection Criteria
- Establish Normalized Figures of Merits for Criteria Ratings
- Rate Propulsion System Concepts
- Multiply Ratings With Weighting Factors
- Sum Products for Each Propulsion System Concept
- Rank Propulsion Systems Concepts According to Magnitude of Magnitude of Product Sums
- Determine Rating Sensitivities
- Review and Reassess Ranking Results

Table 5. SSPS Selection

- Reliability and Safety
  - Simplicity of Concept
  - Number of Components
  - Number/Severity of Potential Safety Hazards
  - Operating Procedure Complexity
  - Number of Life/MTBF Limiting Components
- Contamination Potential
  - Exhaust Plume Impingement
  - Effluent Contamination Potential
  - Plume Radiation and Optical Effects
- Technical Risk
  - Technology Readiness
  - Technology Uncertainty
  - Sensitivity to Space Station Configuration
- IOC and Life Cycle Cost
  - IOC (Phase C/D) Cost
  - Life Cycle Cost
- Growth Potential
  - Ease of Modular Upgrading
  - Cost of Scarring for Growth
  - Integration with Growth Space Station
- Operational Utility
  - Launch Packaging
  - Ease of Deployment
  - Refueling Mode
  - Ease of Repair/Restoration
- Potential SSPE Integration
  - Propulsion System Energy Requirement
  - Interaction With Other Space Station Subsystems

SELECTION CRITERIA WEIGHTING FACTORS

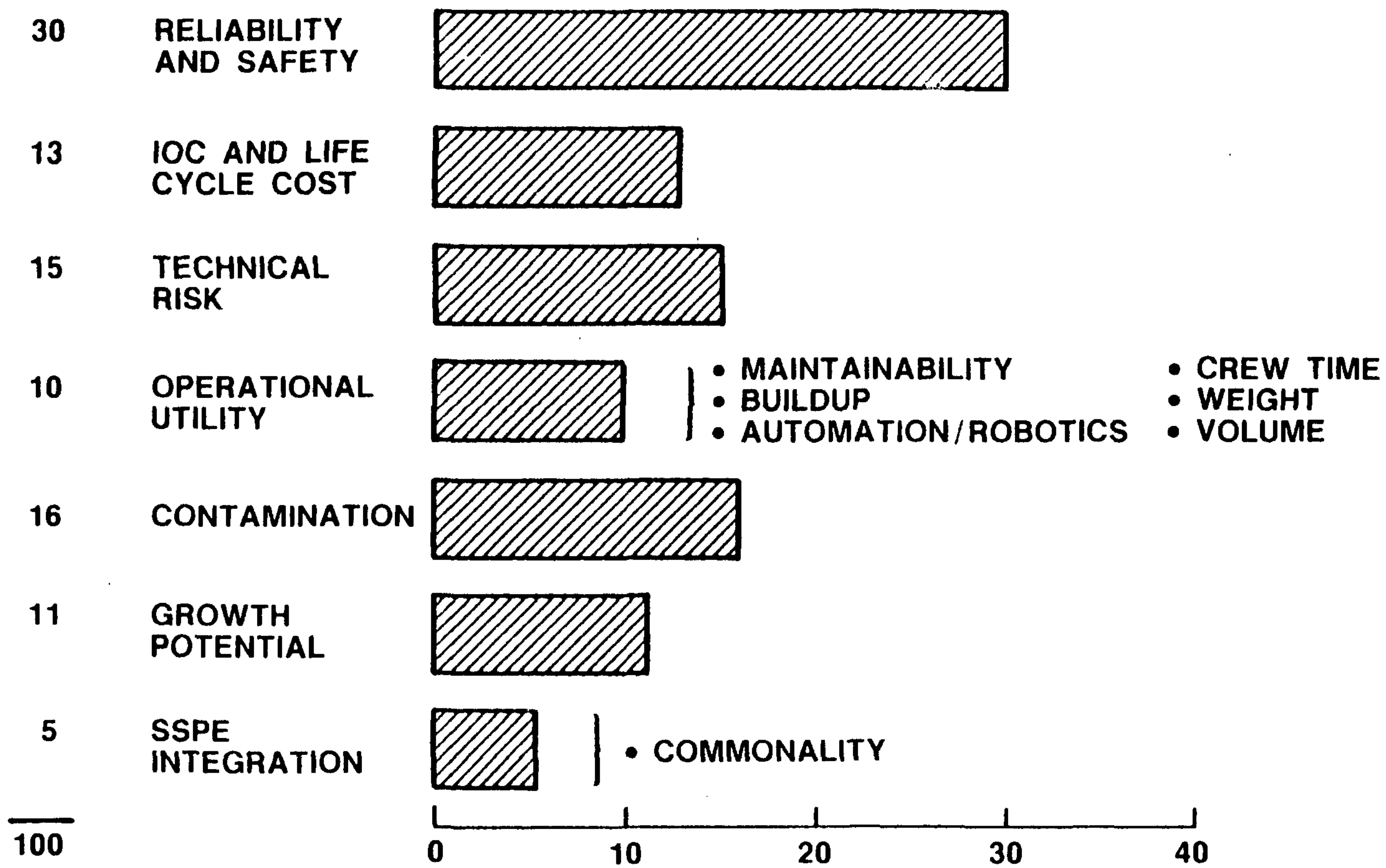

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Figure 8

factors is determined by performing the same process with all the criteria weighting factor equal. Finally, the ranking of the candidate systems is reviewed and assessed and used to support the chosen candidate systems for recommendation.

Based on the simple candidate system schematics presented previously, the fail operational/fail safe requirement, and the utilization of operational maintainability, a detailed schematic was prepared for each candidate system. As a representative sample, the detailed schematics of the O_2/H_2 and the warm H_2 candidate system are presented in Figures 9 and 10. As illustrated in these figures, major components, valves, regulators, and quick disconnects are shown as well as the component redundancy. The propellant supply was divided into three modules. For the reference total impulse, one module was the 90-day supply and the other two modules were the contingency propellant. Propellant supply tank pressurization was provided by electrical heating. All propellant tanks are pressurized to a pressure above their respective critical pressure (supercritical pressure). Heat exchangers were used to condition the propellant in the accumulator.

To provide data for the evaluation of the different candidate systems, the total system weight and volume were determined using the preliminary system design computer code. This computer code can design up to twenty- eight different candidate systems with its variable schematic capability. Propellant flows, pressures, temperature, and component weights and volumes are determined. The system volume is computed and consisted of resupply and contingency propellant tanks, and the accumulators. Also, the total system weight is calculated and includes the propellant (90-day plus contingency) and all other components (tanks, lines, valves, heat exchangers, accumulators, pressure regulators, quick disconnects, and instrumentation). The resupply weight consisted of the 90-day resupplied propellant, tanks, instrumentation, and associated plumbing.

A study was conducted to determine the appropriate object function for system optimization. Factors such as initial cost (volume/weight), resupply cost

O_2/H_2 SYSTEM

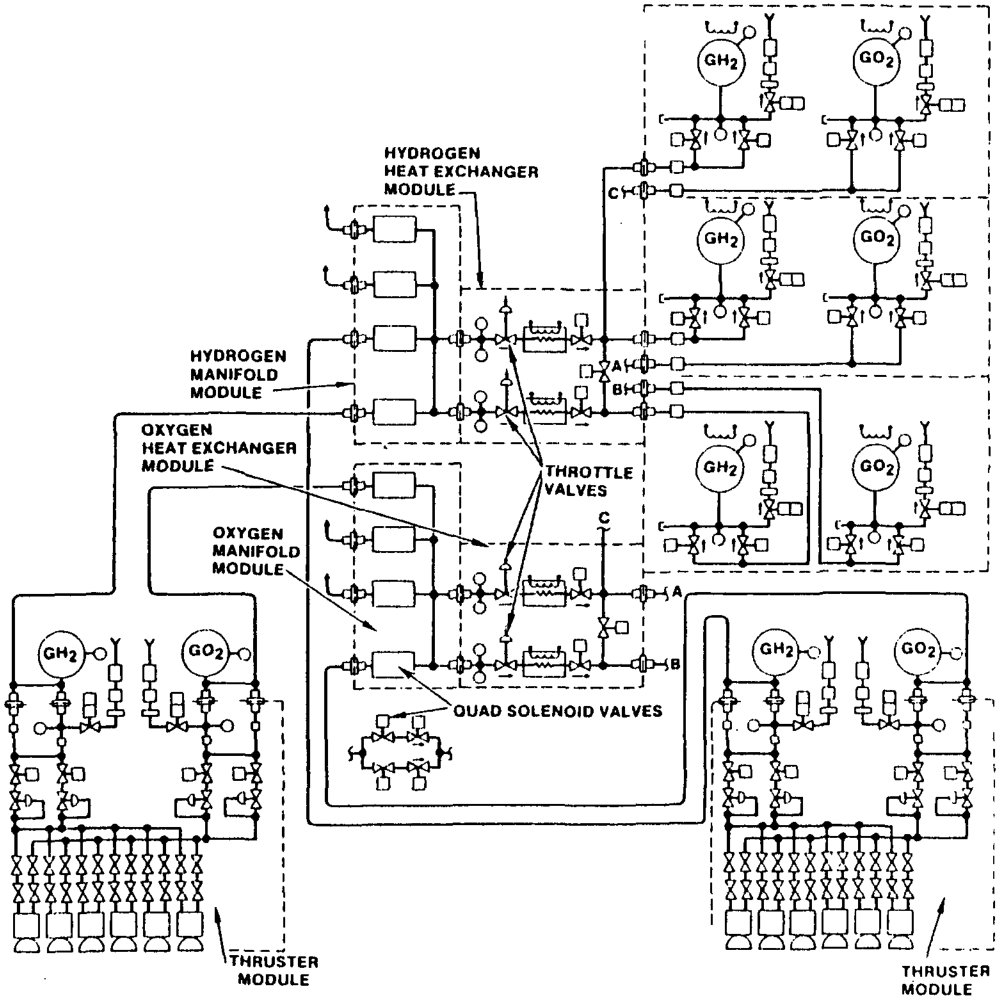

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Figure 9

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WARM H_2 SYSTEM

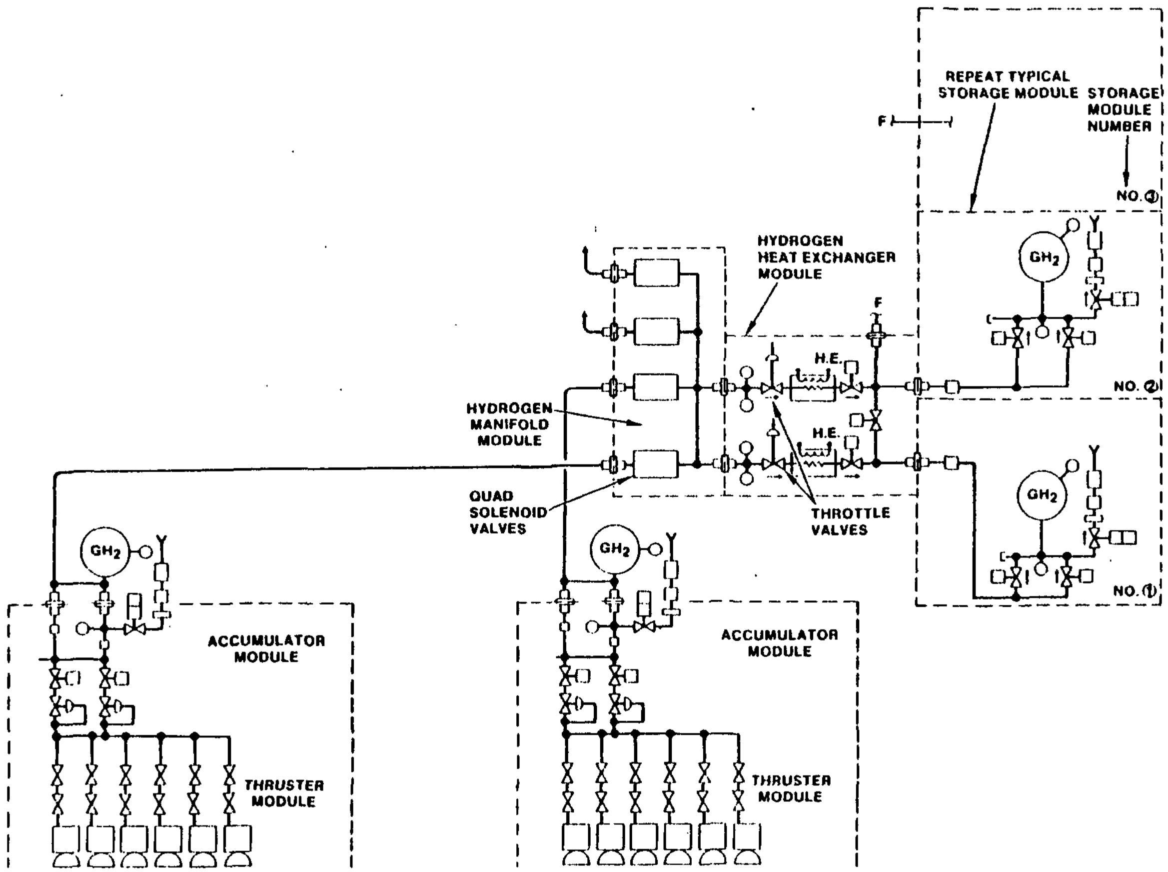

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Figure 10

(resupply weight) and combination of these were examined. Minimization of total weight provided a system close to minimum IOC cost and resupply cost with reasonable volume. Each candidate system was designed for each of the two total impulses and optimized for minimum total wet system weight. Total system weight will directly influence the production and initial launch cost, and the resupply weight will impact the operational costs. Propellant tank pressure, accumulator size, accumulator pressure and temperature range, and thruster chamber pressure were varied internal to the computer code to obtain a minimum system wet weight.

In addition to total impulses previously presented in Table 1 and the overall assumptions in Table 3, the detailed assumptions used in this evaluation are shown in Table 6. Preliminary designs were obtained for each of the eight candidate systems. The general trends in the optimization included lower chamber pressures and increases in area ratio. To reduce the propellant tank and accumulator weights, lower pressures were desirable but pressures were maintained above the respective fuel and oxidizer critical pressures. The resulting normalized (O_2/H_2 system chosen as the reference) total system and resupply weight and volume are presented in Figures 11 through 14. The O_2/H_2 system resulted in the lowest total system and resupply weight and volume. The O_2/H_2 system integrated with the ECLSS using CO_2 resistojets resulted in a lower resupply volume due to the utilization of on-board CO_2. The O_2/H_2 system with water electrolysis resulted in the highest total system weight. Since immediately after the initial station deployment, this candidate system cannot provide sufficient propellant for reboost, propellant and high pressure tanks were incorporated in the system to provide for the initial station reboost. Subsequently, the propellants are generated and stored. The warm H_2 system has the highest total system and resupply volume and the highest resupply weight.

The total energy required (propellant tank pressurization, propellant thermal conditioning, resistojet power, and water electrolysis power) for each of the candidate systems is presented in Figure 15. The crosshatched portion of each bar represents the energy required to pressurize the propellant tanks for

Table 6. System Evaluating Assumptions

• Supercritical Propellant Storage Except for Water Electrolysis		
• Tank and Accumulator Material		
• Fuel Tank and Accumulator	Aluminum 2219-T62	
• Oxidizer Tank and Accumulator	Inconel 718	
• ECLSS Influenced Impulses		
• CO_2 Resistojet		
• Total Available Impulse	154,440 lb-sec	
• Specific Impulse	130 lbf-sec/lbm	
• Number of Tank Charges	3	
• CH_4 Resistojet		
• Total Available Impulse	69,120 lb-sec	
• Specific Impulse	160 lbf-sec/lbm	
• Number of Tank Charges	3	
• Combined Alternate System Impulse	Reference	Proposed
• Drag Makeup (Oxygen/Hydrogen)		
• 90 Days, lb-sec	483,000	854,000
• Contingency, lb-sec	892,000	155,000
• Attitude Control (Warm H_2)		
• 90 days, lb-sec	26,000	370,000
• Contingency, lb-sec	147,000	280,000
• Oxygen/Hydrogen System		
• Mixture Ratio	4 to 1	
• Minimum Thruster Inlet Temp.		
• Hydrogen	200 R	
• Oxygen	400 R	
• Water Electrolysis System		
• Mixture Ratio (Oxygen/Hydrogen)	8 to 1	
• Tank Design Temperature	500 R	
• Tank Design Pressure	3000 psia	

NORMALIZED WEIGHT COMPARISON-SYSTEM CANDIDATES
90 DAYS AND CONTINGENCY

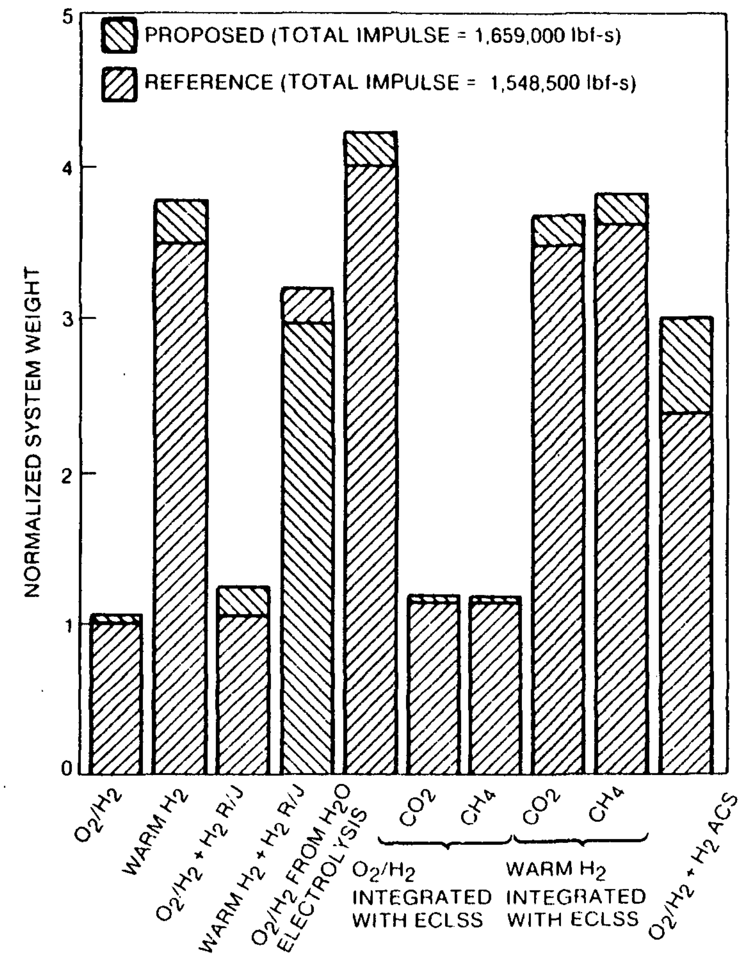

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Figure 11

NORMALIZED VOLUME COMPARISON-SYSTEM CANDIDATES

90 DAYS AND CONTINGENCY

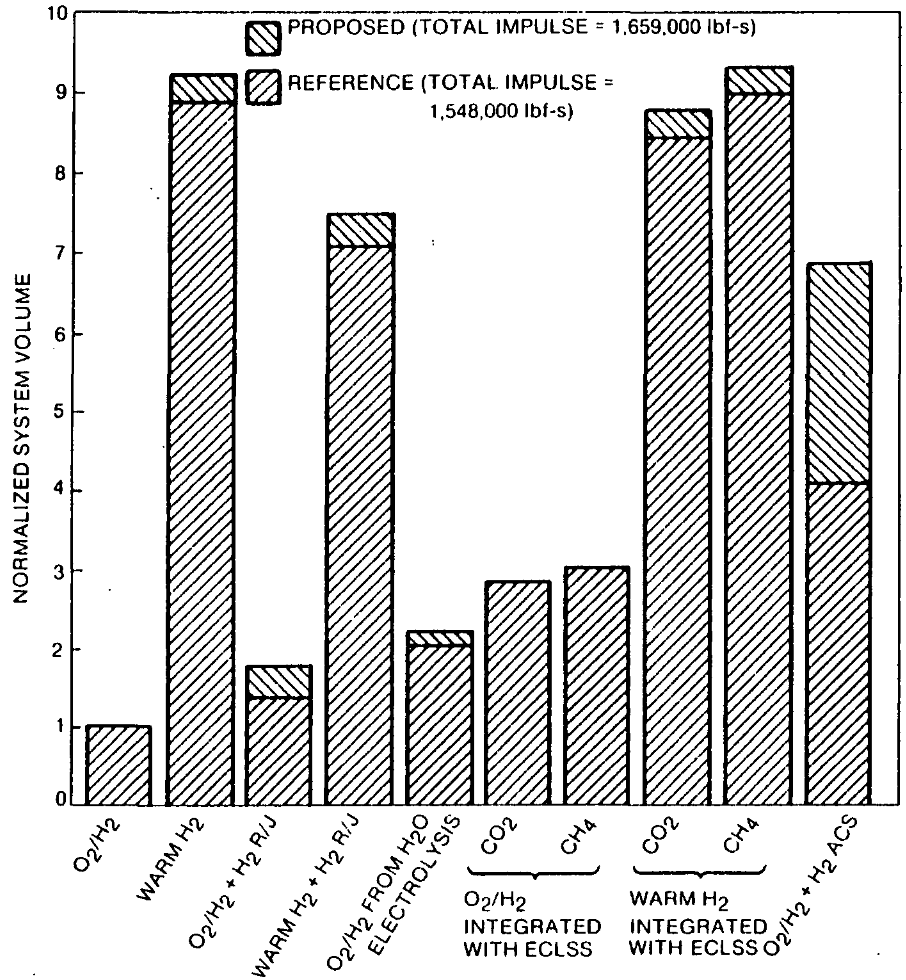

Figure 12

NORMALIZED RESUPPLY WEIGHT COMPARISON-SYSTEM CANDIDATES

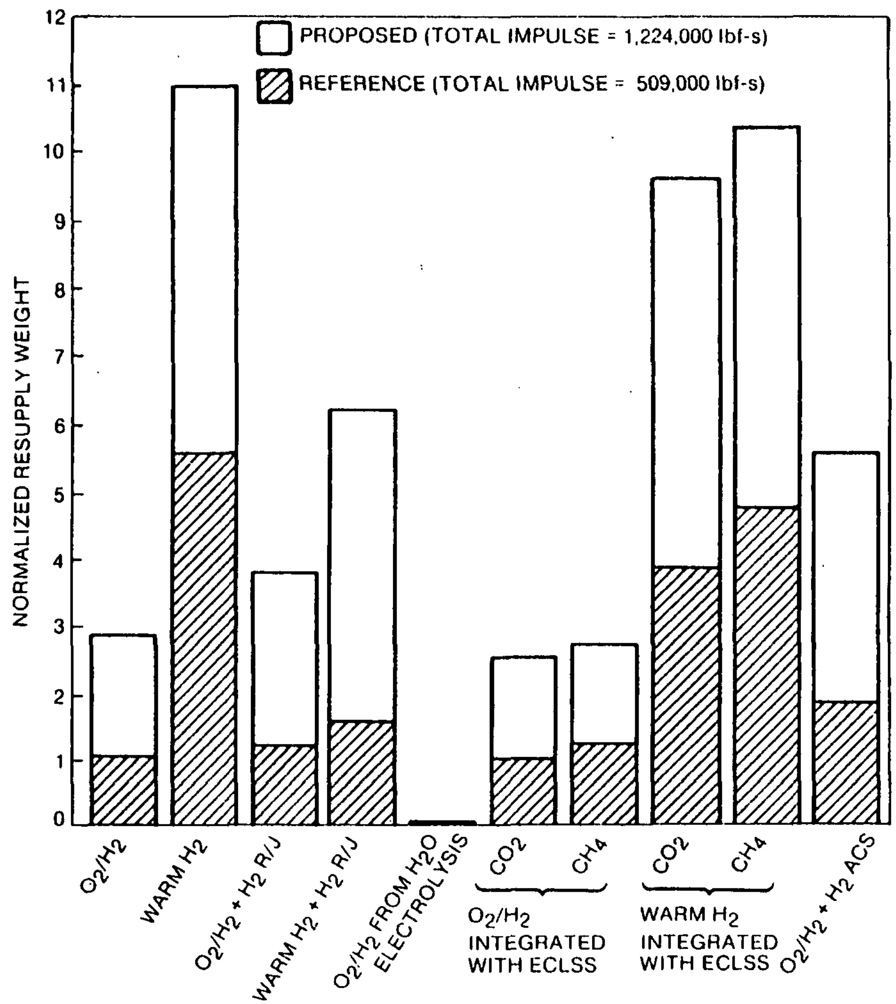

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Figure 13

NORMALIZED RESUPPLY VOLUME COMPARISON- SYSTEM CANDIDATES

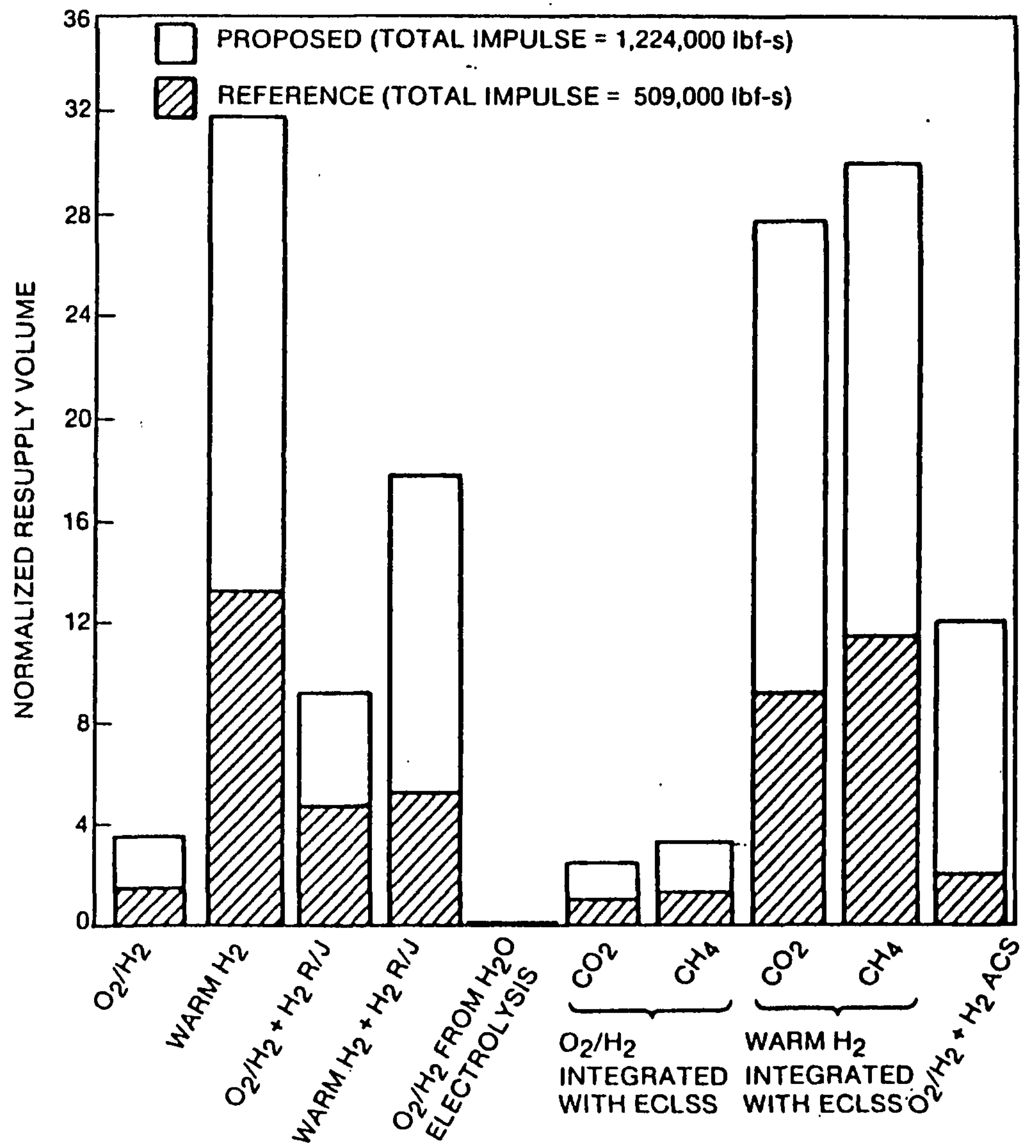

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Figure 14

TOTAL ENERGY COMPARISON

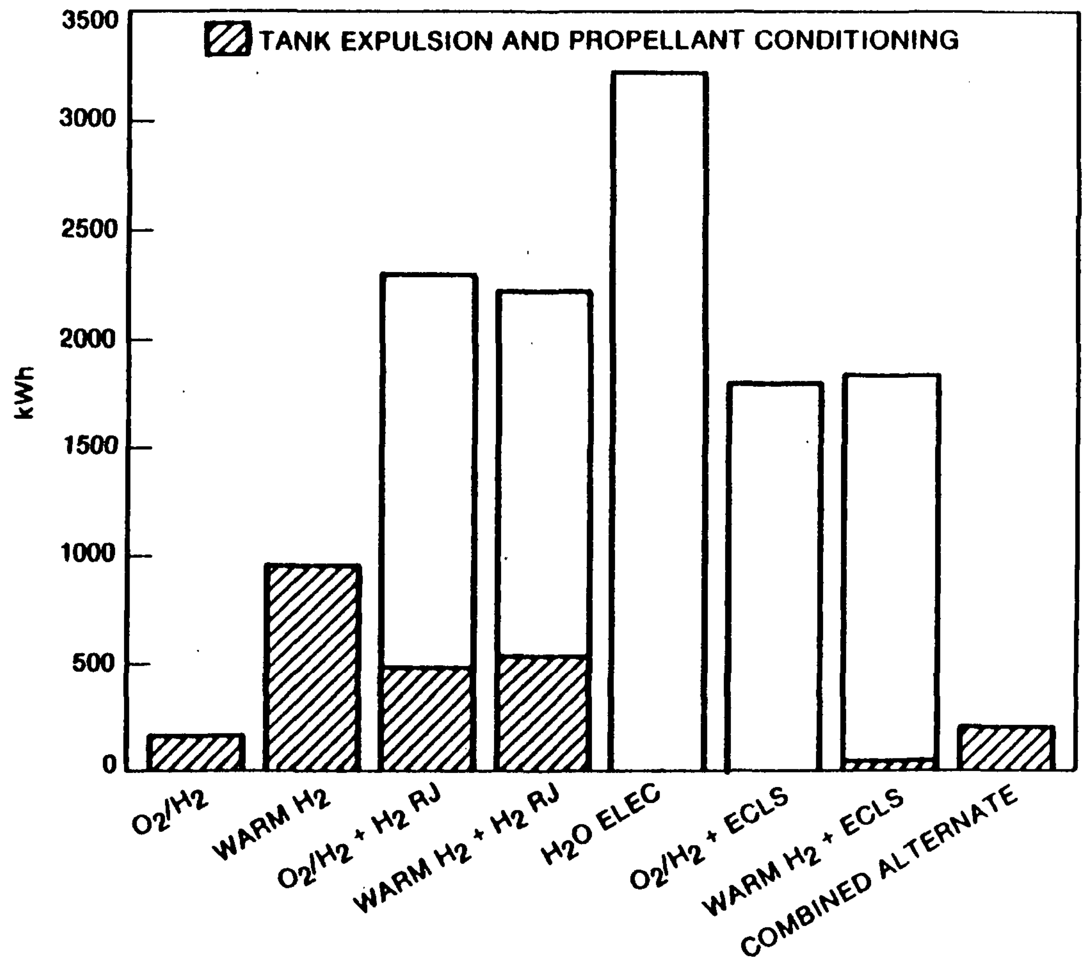

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Figure 15

expulsion and thermally condition the propellants. The open portion of the bar is either the energy required for resistojets or for water electrolysis. The O_2/H_2 system resulted in the lowest total energy requirement. The water electrolysis system had the highest total energy requirement due to the energy required for electrolysis although the peak power was low.

In the following sections, each candidate system is evaluated and compared with respect to each of the seven selection criteria.

Reliability/Safety. The assessment of the reliability of each candidate system involved the determination of the total number of components (both active and passive), the total number of active components, and total number of active components with limited life. In general, system complexity and unreliability will increase with the total number of components and with the total number of active components. As shown in Table 7, the warm H_2 system contained the lowest number of components and the O_2/H_2 system integrated with the Environmental Control and Life Support System (ECLSS) contained the largest number of components. Similarly, when the number of active components were considered (Table 7), the warm H_2 system resulted in the lowest number. The O_2/H_2 system with the H_2 resistojets had the largest number of active components. As expected, the systems using only hydrogen had less total components and less active components than the O_2/H_2 systems.

Also, the system reliability is related to the use time divided by the Mean Time Between Failure (MTBF). Again, as shown in Table 8, the warm H_2 system had the lowest number of active components with limited life (higher reliability rating) and the O_2/H_2 system integrated with the ECLSS had the largest number.

A general overall reliability assessment was that the candidate systems containing only hydrogen had a higher reliability rating than candidates incorporating oxygen and hydrogen.

Table 7. Component Count

Candidate System	Total Number of Components (Active and Standby)	Total Number of Active Components
1 O_2/H_2	215	128
2 Warm H_2	119	76
3 O_2/H_2 + H_2 Resistojet	230	175
4 Warm H_2 + H_2 Resistojet	157	89
5 O_2/H_2 From Electrolysis	132 (plus electrolysis)	79 (plus electrolysis)
6 O_2/H_2 With ECLSS	272	156
7 H_2 With ECLSS	171	97
8 Warm H_2 ACS + O_2/H_2 Reboost	188	114

Table 8. Number of Active Components With Potentially Limited Life/MTBF

Space Station Propulsion System Candidate	A Oxygen Tank Heaters	B Thrusters	C Regulators Throttle Valves	D Oxygen Heat Exchangers	E Latching Valves	F Automatic QDs	G Electrolysis Units	A through G Total	A + D + F Components With High MTBF
Oxygen/Hydrogen	1	24	10	1	38	6	–	81	8
Warm Hydrogen	–	24	5	–	19	3	–	51	3
Oxygen/Hydrogen + Hydrogen Resistojet	1	24	14	1	40	6	–	86	8
Warm Hydrogen + Hydrogen Resistojet	–	24	9	–	19	3	–	55	3
Oxygen/Hydrogen from Electrolysis	–	24	8	–	31	1	2	63 (plus 2 electrolysis)	2 electrolysis
Oxygen/Hydrogen with ECLSS	1	32	14	1	48	6	–	102	8
Hydrogen with ECLSS	–	32	9	–	29	3	–	73	3
Warm Hydrogen ACS + Oxygen/Hydrogen Reboost	1	28	8	1	30	6	–	74	8

The safety assessment identified potential major safety hazards and their corresponding inhibitors. The potential safety hazards identified were over-heating of the oxygen tanks and oxygen heat exchangers and overpressurization of the propellant tanks. The occurrence of these failures are believed to be highly unlikely with the controls envisioned to monitor the system operation and the hardware condition. Inhibitors to minimize the potential of these hazards were primarily associated with design provisions such as relief valves, leak-before-burst criteria and large safety factors and with instrumentation, redundant controls, and the hardware "health"-monitoring system.

Therefore, in general, the candidate systems which use only hydrogen resulted in a higher reliability and safety rating than the systems using oxygen and hydrogen.

Contamination Potential. During overall quiescent operation of the Space Station, external contamination requirements stipulate limits on molecular column densities, background light levels, particle releases and deposits of matter generated on the station. Many optical payloads on the station are sensitive to non-transparent gases made up of molecules or particles which absorb in the visible, infra-red or ultra-violet parts of the spectrum. Telescopes and related equipment must avoid deposits of condensed materials on mirrors. Electromagnetic contamination in the form of electric and magnetic fields can also affect susceptible sensors.

Figure 1.6 shows the sources contributing to the total external contamination environment, the SSPS being just one source of many. The most significant releases are from the docking of the Space Shuttle Orbiter on station resupply trips. Also, the atmospheric atomic oxygen prevalent at LEO is quite severe on material surfaces. An important factor in minimizing contamination effects due to the propulsion system is the proper scheduling of drag makeup thrusting vis-a-vis observations from attached payloads and the optimum placement of

TOTAL SPACE STATION EXTERNAL ENVIRONMENT

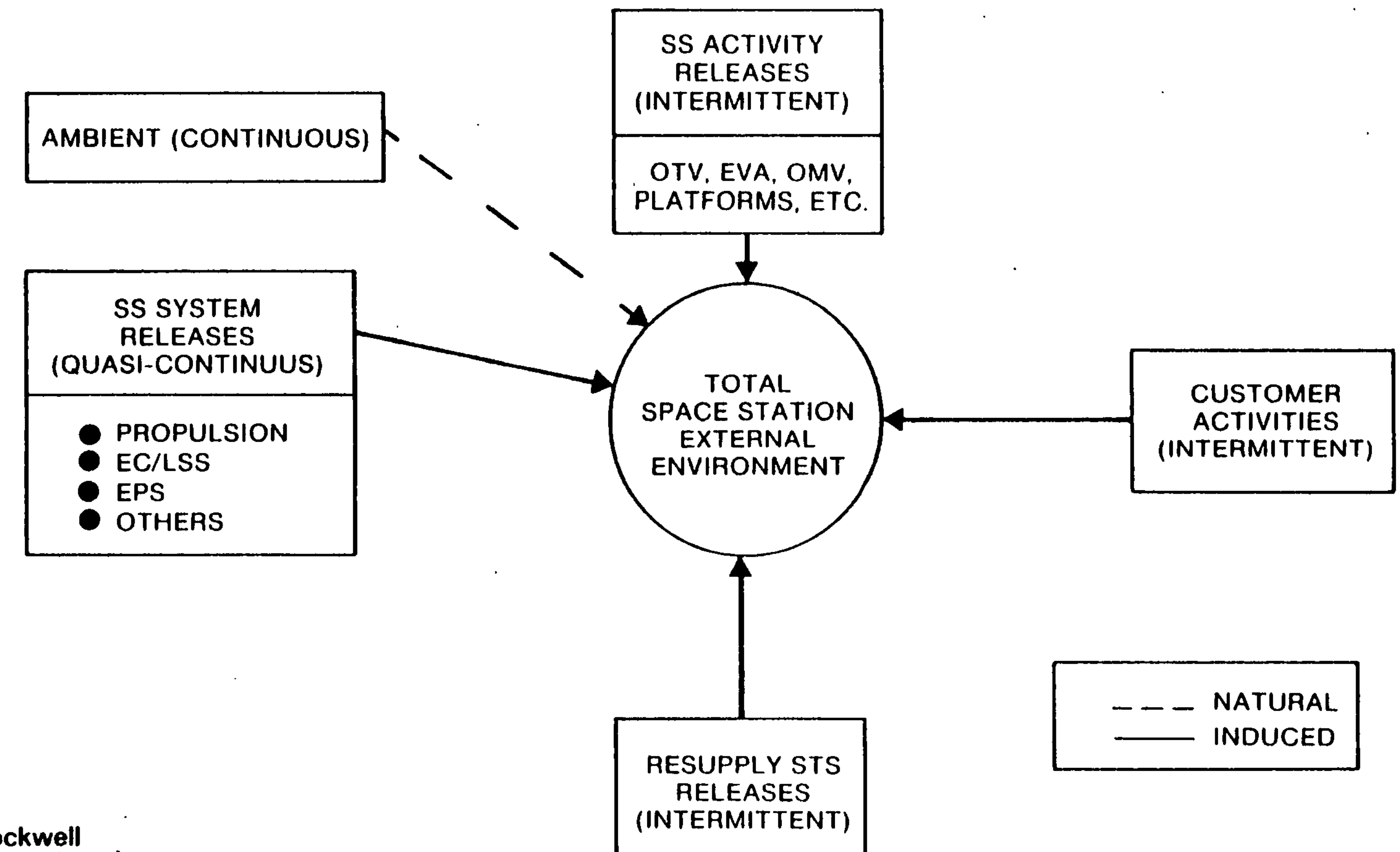

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Figure 16

thruster modules for least plume impact on station surfaces. For instance, the Solar Observatory Telescope (SOT) can only see the sun about one hour in each 1.5-hour orbit; other operations can be performed in the dark portion of the orbit where there is no interference with the SOT.

The contamination potential of a propulsion system depends on the following factors:

Propellants → Thruster Effluent Species →	• Molecular Species Column Densities • IR Absorption • Condensed Water
Propellant Flowrate → Thruster Plume Density →	• Molecular Total Column Densities
Thrust Level and Thruster Nozzle Design → Backflow →	• Impingement

For the candidate propulsion systems, a number of evaluations were conducted. The dominant thruster effluent species and their relative amounts were determined for each system. The potential of the occurrence of thrust backflow was qualitatively assessed. Thruster backflow can cause plume impingement and deposition and/or condensation of the effluent on station surfaces. For this study, it was assumed that free-molecular flow nozzles for resistojets were feasible; therefore, no backflow would occur for a resistojet. Based on the thruster effluent species and the properties of the individual species, the potential of each specie for condensing on a surface was determined. Also, the absorption spectrum was obtained for each effluent species over the infrared wavelength range.

The comparative results of the contamination potential evaluation are presented in Table 9. In general, the candidate systems using only hydrogen have a lower contamination potential than the O_2/H_2 systems or the systems containing CO_2 or CH_4 resistojets. Although a hydrogen thruster can result in some thruster backflow, the hydrogen condensation temperature is so low (7.2°R) at vacuum conditions that condensation will not occur. Also, hydrogen does not appreciably absorb in the infrared spectra.

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Technical Risk. Technical risk assessment conducted consisted of identifying the technology issues associated with each candidate system and a resolution of the critical nature of each identified issue. For the eight candidate systems, a total of five generic technology issues were defined. These included: (1) complex control system; (2) tank heating and gauging; (3) resistojet life; (4) water rocket life; and (5) electrolysis unit issues.

The control system issues involve the accumulator propellant mass gauging error, transport delay in control loop due to long propellant lines, and the potential of the heat of compression contributing to accumulator overpressurization. The assessment of these technology issues was that these issues were not considered critical since technology exists to resolve the identified control system issues.

The propellant tank heating and gauging issue identified for supercritical pressure propellant storage was zero gravity propellant stratification influencing the propellant heating and mass gauging. This issue was not believed to be critical since only very small gravity level will avert stratification.

The technical issues associated with resistojets were the life of the thruster with different propellants, specifically the heating element, and the fact the resistojet free molecular flow has not been demonstrated. The longest demonstrated resistojet life has been in the 500 to 1000-hour range. These issues can and should be resolved prior to IOC if resistojets are to be incorporated in the IOC SSPS.

Thrusters (water rockets) using oxygen and hydrogen from electrolyzed water (mixture ratio of 8) have a number of technical issues which can be resolved with current technology. The high mixture ratio of the water rocket results in a lower delivered specific impulse and therefore will require a higher propellant weight (resupplied water if a dedicated water electrolysis is used) than conventional oxygen/hydrogen. The combustion at this stoichiometric

mixture ratio results in a higher combustion temperature than at conventional oxygen/hydrogen mixture ratios which requires the use of additional cooling. A long life water rocket has not been demonstrated but can be easily tested in NASA-MSFC's SSPS test bed. The technical issues identified with a water electrolysis unit were primarily related to system complexity. System complexity concerns included the need for a deionizer for the acceptance of all types of water, the need for dryers to remove entrained moisture in the product gas streams, and potential deterioration of cell electrochemical components. Long life of high pressure electrolysis units has already been demonstrated in submarines and the development of units for ECLSS and electrical energy storage is proceeding under NASA aegis.

A summary of the identified technology issues is presented in Table 10. The single check (✓) in the control system and the tank heating and gauging columns indicates that only one propellant need be considered for the candidate systems using only hydrogen. As indicated in Table 10, the warm hydrogen system resulted in the least number technology issues and the O_2/H_2 system with resistojets and the O_2/H_2 system integrated with ECLSS resulted in the most technology issues.

Cost. Life Cycle Costs (LCCs) for the eight propulsion system candidates were determined using Rocketdyne's LCC program (SSPSLCC). This LCC model was developed specifically for the space station propulsion system to support the ongoing requirement and configuration trade studies. The model was conceived to be flexible in its structure in order to handle the large variations in propulsion concepts with regard to propellants, hardware, space station characteristics and operational support schemes.

The model categorizes LCC into four cost segments, i.e., development, production, transportation and operational support. The methodology also includes cost risk. The results of the cost analysis are illustrated in

Table 10. Candidate System Technology Issues

System Number	Complex Control System	Tank Heating and Gauging	Resistojet Life	Water Rocket Life	Electrolysis Unit Issues
1	✓✓	✓✓			
2	✓	✓			
3	✓✓	✓✓	✓✓		
4	✓	✓	✓✓		
5				✓✓	✓✓
6	✓✓	✓✓	✓✓		
7	✓	✓	✓✓		
8	✓✓	✓✓			

Figure 17. Configurations using H_2 as a monopropellant have the lowest IOC cost, but the highest LCC. On the other side, the O_2/H_2 system with electrolysis has the highest initial cost but the lowest LCC, especially if all the water can be supplied by the space station as waste water. The high IOC cost of this latter candidate system was due to the inclusion of propulsion dedicated electrolysis unit development, production, and system integration costs. If any or all of these costs are shared with other space station subsystems, or if further cost refinements reduce these costs, substantial reductions in IOC cost may be achieved. In any case, this candidate system will still have the lowest LCC.

A self-sufficient Space Station wherein all fluids are reprocessed and recirculated, and fluid resupply from earth is minimized, is the ultimate stated goal of the Space Station and is in tune with the Design-to-LCC (DTLCC) approach adopted for the Space Station Program decision-making process.

Table 11 presents the IOC (or Phase C/D) and LCC drivers for each of the eight configurations. Control system (including health-monitoring), cryogenic tank development, and electrolysis are IOC cost drivers, while fluid resupply is in all cases (except the electrolysis configuration) the LCC driver. A typical LCC breakdown for the O_2/H_2 system of Configuration 1 is shown in Figure 18. Next to fluid resupply (i.e., transportation) cost, the development (RDT&E) cost is the largest contributor to LCC for this system.

From the cost analysis, it was concluded that (1) all warm H_2 system candidates have the lowest IOC costs, (2) the O_2/H_2 candidates have lower LCC if propellants are supplied from earth, and (3) O_2/H_2 with electrolysis has the lowest LCC of all configurations and is the most attractive system with respect to LCC when water is Space Station-supplied. Candidates with CO_2 resistojets were found to have lower LCC than those with the technically more difficult CH_4 resistojets.

SSPS COST RESULTS

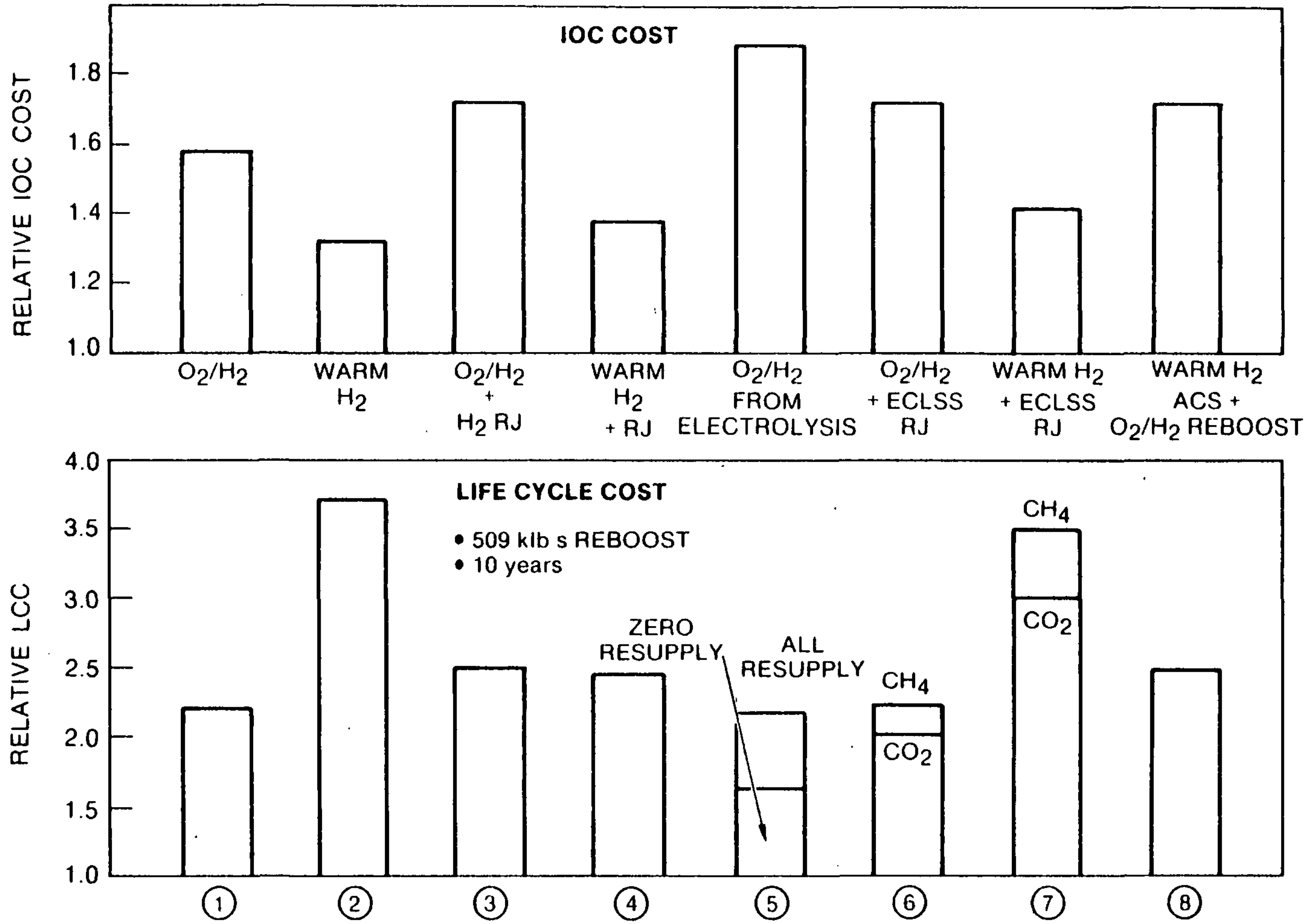

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Figure 17

Table 11. Cost Driver Comparison

SSPS Candidate System	IOC Cost Drivers	LCC Drivers
1 O_2/H_2	• Tank Development • Control System	• Fluid Supply
2 Warm H_2	• Control System • Tank Hardware	• Fluid Resupply • Initial Placement
3 O_2/H_2 + H_2 Resistojet	• Tank Development • Control System • Tank Hardware	• Fluid Resupply
4 Warm H_2 + H_2 Resistojet	• Control System • Tank Hardware	• Fluid Resupply
5 O_2/H_2 From Water Electrolysis	• Control System • Electrolysis Unit • Tank Development	• Fluid Resupply • Initial Placement
6 O_2/H_2 With ECLSS	• Control System • Tank Development • Resistojet Development	• Fluid Resupply • Replacement Hardware Transport.
7 Warm H_2 With ECLSS	• Control System • Tank Hardware	• Fluid Resupply • Initial Placement • Replacement Hardware Transport.
8 Warm H_2 ACS + O_2/H_2 Reboost	• Control System • Tank Development	• Fluid Resupply

LIFE CYCLE COST BREAKDOWN
O_2/H_2
CONFIGURATION 1

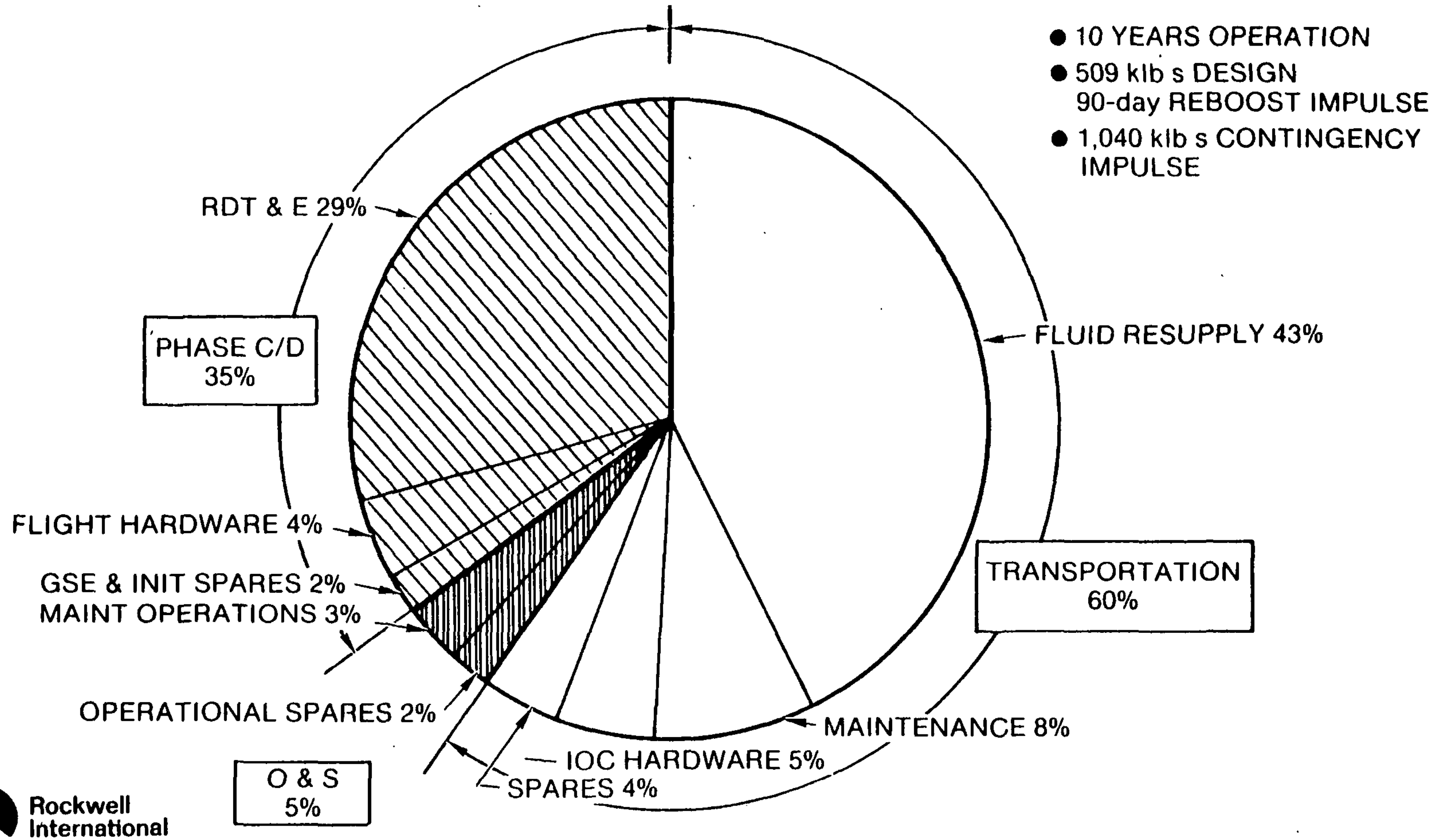

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Figure 18

Growth Potential. The growth of the space station can take on different dimensions. Potentially the dimensions can include: (1) higher total impulse requirement due to a large electrical power system projected surface area; (2) higher propulsion system performance to reduce system resupply weight; (3) integration of the propulsion system with other space station systems; (4) reduced contamination; and (5) improved operational features.

Although the configuration of the growth station cannot be quantified at this time, the direction will be to minimize resupplied propellant and utilize waste products. This direction will lead to the full utilization of ECLSS waste products, OTV propellant depot boiloff, manufacturing process wastes, and water electrolysis. The potential on-board propellant sources, the produced propellant and the potential growth propulsion systems are presented in Table 12. A representative O_2/H_2 system growth path is illustrated in Figure 19. The initial system in this example is a supercritical O_2/H_2 system which transforms into a water electrolysis O_2/H_2 system and then to a fully integrated O_2/H_2 system with multipropellant resistojet being supplied propellant from the on-board sources.

The growth potential criteria considered included ease of modular upgrading, ease of integration with other station systems, and the relative cost of scarring. As shown in Table 13, the candidate systems with minimal integration with other space station systems (O_2/H_2, warm H_2, O_2/H_2 with H_2 resistojets, warm H_2 with H_2 resistojets, and warm H_2 ACS with O_2/H_2 drag makeup) were the easiest to upgrade modularly. Conversely, the candidate systems with the more space station system integration (O_2/H_2 system with dedicated water electrolysis, O_2/H_2 system integrated with ECLSS, and the warm H_2 system integrated with ECLSS) would result in easier space station integration and lower station scarring cost.

Table 12 SSPS Growth Direction

Potential Space Station On-Board Propellant Sources	Propellants	Potential Growth SSPS
Water Electrolysis	O_2 and H_2	O_2/H_2 with H_2
OTV Propellant Depot and EPS SAVE Haven Boiloff	H_2 and Possibly O_2	
ECLSS Manufacturing Processes	CO_2 or CH_4, Water, and/or Other Gases	CO_2, CH_4, or Other Gas Resistojets

REPRESENTATIVE O_2/H_2 SSPS GROWTH PATH

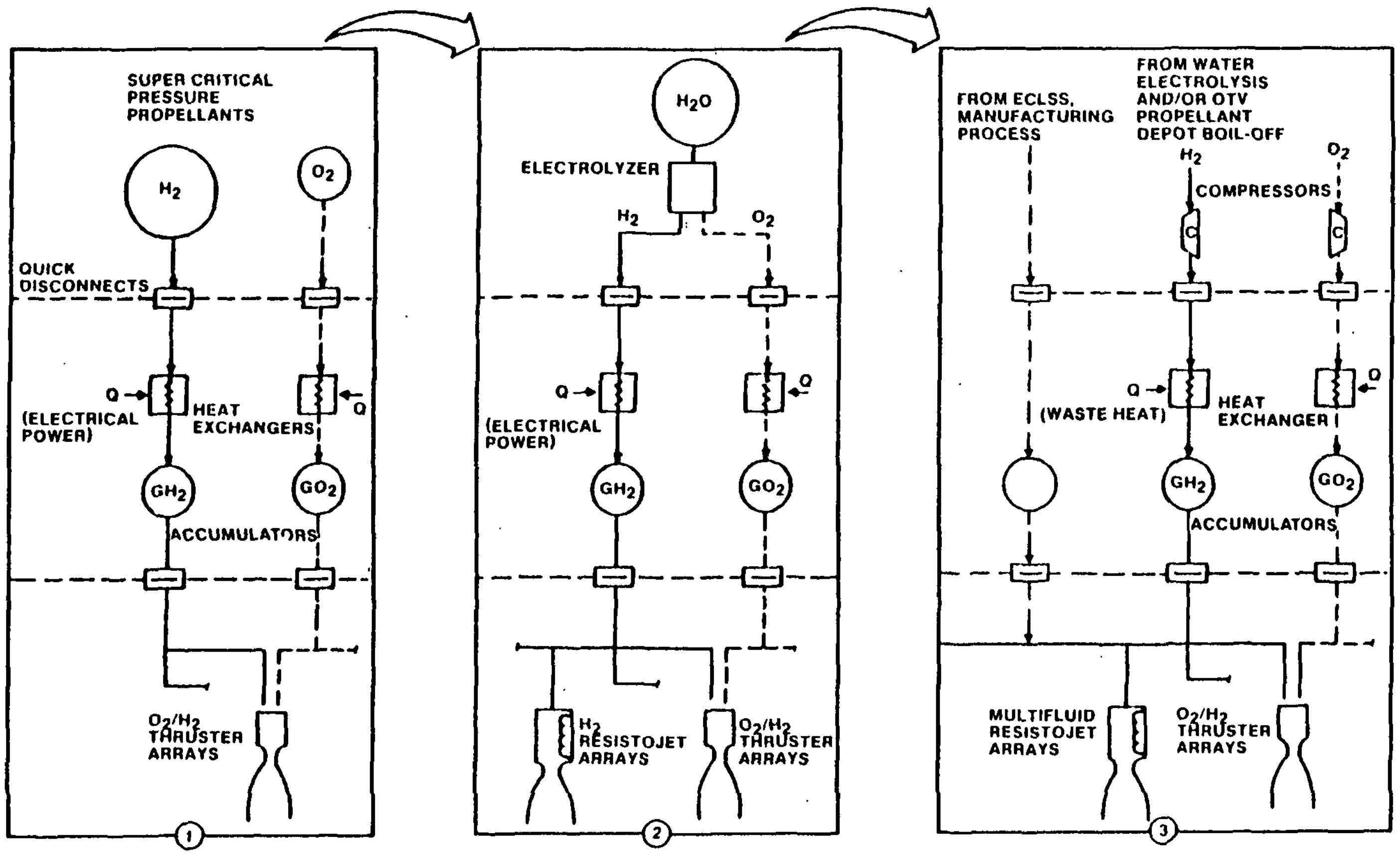

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Figure 19

Table 13. SSPS Growth Potential Assessment

Growth Potential Criteria	Evaluation Result	Comments
• Ease of Modular Upgrading • Increased Total Impulse	• Easy: O_2/H_2, warm H_2, O_2/H_2 with H_2 resistojets, warm H_2 with resistojets, and combined alternate	• Simply add more or larger propellant tanks
	• Some Difficulty: O_2/H_2 and warm H_2 integrated with ECLSS	• Requires significantly more electrical power
	• More Difficult: O_2/H_2 from water electrolysis	• Substantially more electrical power consumption
• Relative Cost of Scarring	• Lower: O_2/H_2 with H_2 resistojets, warm H_2 with H_2 resistojets, O_2/H_2 from water electrolysis, O_2/H_2 and warm H_2 integrated with ECLSS	• Minimal system modifications
	• Higher: O_2/H_2, warm H_2, and combined alternate	• Requires significant system modifications (multifluid) resistojet, ECLSS integration
• Ease of Integration • Other Space Station System	• Easy: O_2/H_2 from water electrolysis, O_2/H_2 and warm H_2 integrated with ECLSS	• Minimal system modifications
• Other SSPEs	• Some Difficulty: Rest of candidate systems	• Requires additional system modifications

Operational Utility. The operational utility assessment considered launch packaging and station keel storage volume, station build-up, propellant availability, ease of initial deployment, refueling complexity, and system maintainability. All the candidate propulsion systems incorporate accumulators near the thrusters and therefore can provide propulsion modules for early space station build-up. Also, all the candidate systems can provide thrust on short notice (propellant availability).

In considering launch packaging and station keel storage volume, the O_2/H_2 candidate systems (referring back to Figures 12 and 14) resulted in the lowest volume requirements. For the initial deployment, the single propellant, warm H_2 system would be the simplest to deploy. The candidate systems which are integrated with the ECLSS or water electrolysis have the most connections and therefore would be the most complex to deploy. The ECLSS integrated candidate systems utilize waste products as propellants and therefore minimize propellant resupplied from earth and simplify propellant resupply. The O_2/H_2 system with dedicated water electrolysis uses inert (safe), high density water resupplied from earth and simplifies propellant resupply.

From a system maintainability standpoint, all candidate systems would be designed for modularity to facilitate maintenance and minimize EVA. Components requiring maximum replacement times include the oxygen tanks, oxygen heat exchangers, and the quick disconnects. The maintenance of oxygen components should be minimized for safety reasons.

In summary, the O_2/H_2 system with dedicated water electrolysis would be the easiest system to maintain (repair and replace). All other O_2/H_2 candidate systems tend to be more complex to maintain.

Potential Space Station Program Element (SSPE) Integration. The assessment of the potential SSPE integration considered the autonomy of the propulsion system candidate with regard to energy needs and resupplied propellant and the potential beneficial interaction with other SSPE systems (ECLSS, Electrical Power System (EPS), manufacturing processes, Orbit Transfer Vehicle (OTV), and platforms). The assessment results are presented in Table 14. From a propulsion system autonomy standpoint, candidates with less hydrogen were more favorable. Hydrogen requires more energy to thermally condition and requires larger and heavier propellant tanks. Considering autonomy, the most favorable candidate systems were the O_2/H_2 system and the O_2/H_2 system integrated with the ECLSS.

The benefit of integrating the propulsion system with other station systems can be significant. For example, integration with the ECLSS and/or manufacturing process can result in utilization of ECLSS or manufacturing waste products and excess water for propulsion propellant. This can significantly reduce resupply costs. The O_2/H_2 and warm H_2 systems integrated with the ECLSS definitely derive benefits from integration with ECLSS, EPS, manufacturing, and the OTV. The O_2/H_2 and the warm H_2 systems could provide commonality with the platforms.

Conclusion and Recommendations

The rating/ranking results of the candidate Space Station Propulsion Systems (SSPS) are summarized in Figure 20 and Tables 15 and 16. As shown in Figure 20, the warm H_2 system achieved the highest overall rating with the warm H_2 system with H_2 resistojets second, the O_2/H_2 system third, the O_2/H_2 water electrolysis system fourth, and the combined warm H_2 ACS and O_2/H_2 reboost system fifth. The order of the rankings remained unchanged with weighted or unweighted factors (Figure 20). Table 15 presents the weighted numerical ratings of each system with respect to all selection criteria. The detailed breakdown to the subcriteria level is presented in Table 16. Therefore, these top five candidate systems were recommended to NASA-MSFC for preliminary design evaluation.

SSPE Integration Criteria	Evaluation Results	Comments
• Propulsion System Autonomy • Minimum Energy Requirements	• Low: O_2/H_2 and combined alternate	• O_2/H_2 energy consumption - low (tank pressurization & thermal conditioning)
	• High: O_2/H_2 from water electrolysis	• Water electrolysis consumes large total energy but at low rate
• Minimum Resupplied Propellants	• Low: O_2/H_2 from water electrolysis if water is free, O_2/H_2, O_2/H_2 integrated with ECLSS	• High performance; smaller and lighter tanks
	• High: Warm H_2	• Low performance; larger and heavier heavier tanks
• Beneficial Interaction with other SSPE Systems		
• ECLSS	• Candidate systems integrated with ECLSS and O_2/H_2 from water electrolysis	• Systems can use ECLSS waste products and/or excess water
• EPS Safe Haven • Commonality	• All candidate systems except O_2/H_2 from water electrolysis	• Systems can use common storage approach
• Use of Boiloff/Vent	• All candidate systems	• Require compressors
• Manufacturing Processes	• Candidate system integrated with ECLSS, O_2/H_2 from water electrolysis and systems with H_2 resistojets	• Wastes used in multifluid resistojets
• OTV Boiloff	• All candidate systems	• Require compressors
• Platform commonality	• Possibly O_2/H_2, warm H_2	• Can not use systems integrated with ECLSS • Large power required for resistojets and water electrolysis

PROPULSION SYSTEM CANDIDATE RATING RESULTS

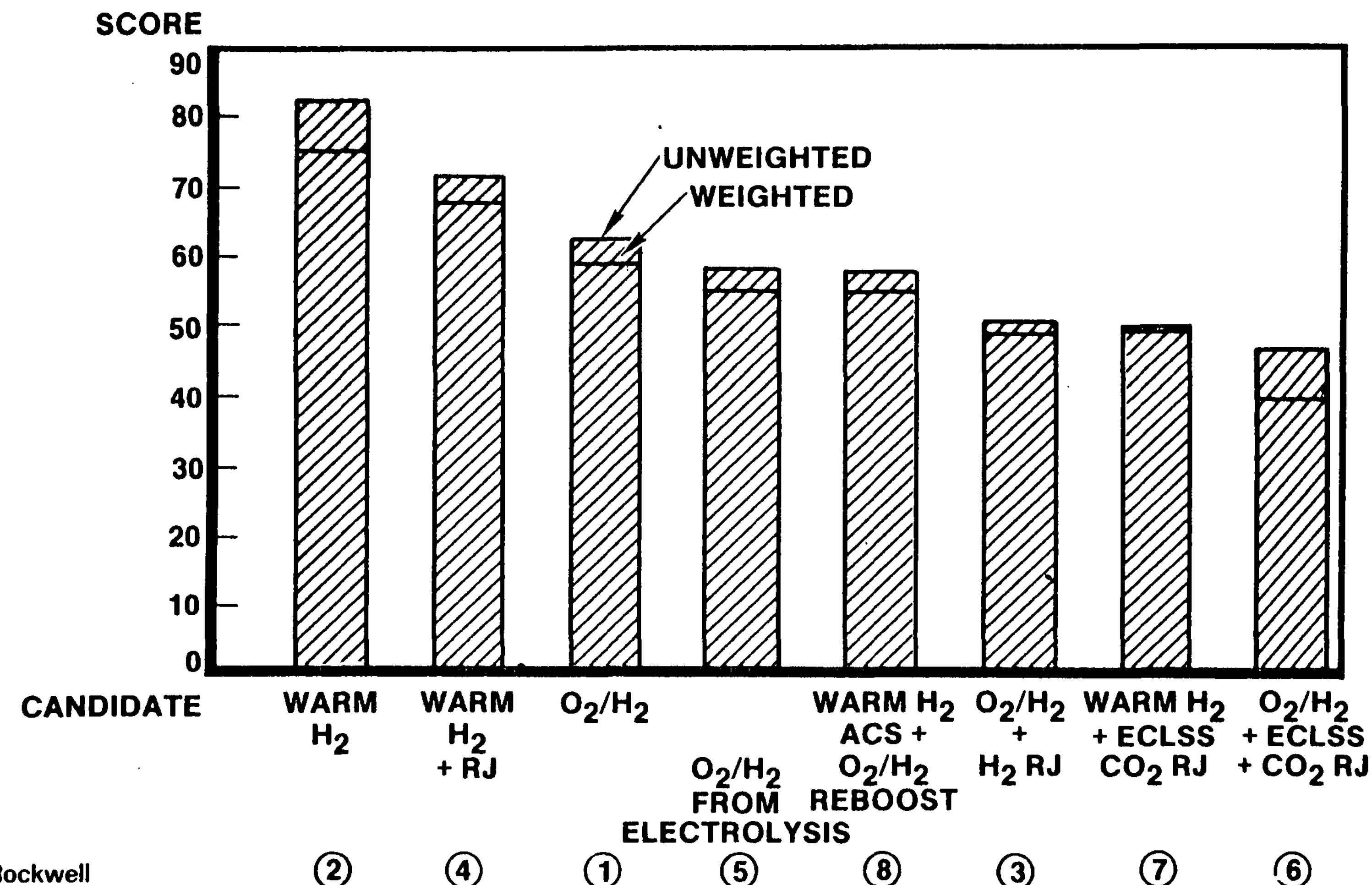

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Figure 20

Table 15. Evaluation Score Summary

Criteria	Wt	System Candidate 1 O_2/H_2	2 Warm H_2	3 O_2/H_2 H_2 RJ	4 Warm H_2 H_2 RJ	5 O_2/H_2 Electrolysis	6 O_2/H_2 CO_2 RJ	7 Warm H_2 CO_2 RJ	8 O_2/H_2 Drag H_2 ACS
Reliability and Safety	30	12.3	29.6	9.8	20.1	13.1	5.3	16.1	13.7
Contamination Potential	16	6.7	16.0	6.7	16.0	6.7	4.0	4.0	6.7
Technical Risk	15	15.0	15.0	10.0	10.0	6.3	5.0	5.0	15.0
IOC and Life Cycle Cost	13	9.2	6.5	6.5	10.5	11.5	8.6	8.1	6.7
Growth Potential	11	6.4	6.4	9.2	9.2	9.2	9.2	9.2	6.4
Operational Utility	10	4.8	4.4	4.8	3.1	7.6	4.8	3.8	3.1
SSPE Integration	5	3.6	3.6	1.5	2.1	1.5	2.5	2.5	3.5
Total	100	58.0	81.5	48.5	71.0	55.9	39.4	48.7	55.1

Criteria	Wt	System Candidate															
		1		2		3		4		5		6		7		8	
		R	WR	R	WR	R	WR	R	WR	R	WR	R	WR	R	WR	R	WR
• Reliability and Safety	30	0.41	12.3	0.99	29.6	0.33	9.8	0.67	20.1	0.44	13.1	0.18	5.3	0.54	16.1	0.46	13.7
• Simplicity of Concept		0.5		1.0		0.25		0.25		0.25		0.25		0.25		0.5	
• Number of Components		0.42		0.95		0.35		0.7		0.65		0.14		0.65		0.52	
• Number/Severity of Potential Safety Hazards		0.25		1.0		0.25		1.0		0.25		0.25		1.0		0.25	
• Operating Procedure Complexity		0.5		1.0		0.5		0.5		0.5		0.25		0.25		0.5	
• Number of Life/MTBF Limiting		0.38		0.98		0.28		0.9		0.54		0.0		0.54		0.52	
• Contamination Potential	16	0.42	6.7	1.0	16.0	0.42	6.7	1.0	16.0	0.42	6.7	0.25	4.0	0.25	4.0	0.42	6.7
• Exhaust Plume Impingement		0.5		1.0		0.5		1.0		0.5		0.25		0.25		0.5	
• Effluent Contamination Potential		0.25		1.0		0.25		1.0		0.25		0.25		0.25		0.25	
• Plume Radiation and Optical Effects		0.5		1.0		0.5		1.0		0.5		0.25		0.25		0.5	
• Technical Risk	15	1.0	15.0	1.0	15.0	0.67	10.0	0.67	10.0	0.42	6.3	0.33	5.0	0.33	5.0	1.0	15.0
• Technology Readiness		1.0		1.0		0.5		0.5		0.5		0.25		0.25		1.0	
• Technology Uncertainty		1.0		1.0		0.5		0.5		0.5		0.25		0.25		1.0	
• Sensitivity to Space Station Configuration		1.0		1.0		1.0		1.0		0.25		0.5		0.5		1.0	
• IOC and Life Cycle Cost	13	0.71	9.2	0.5	6.5	0.5	6.5	0.81	10.5	0.89	11.5	0.66	8.6	0.62	8.1	0.52	6.7
• IOC (Phase C/D) Cost		0.55		1.0		0.3		0.87		0.55		0.32		0.82		0.31	
• Life Cycle Cost		0.87		0.0		0.7		0.74		1.22		1.0		0.42		0.72	
• Growth Potential	11	0.58	6.4	0.58	6.4	0.83	9.2	0.83	9.2	0.83	9.2	0.83	9.2	0.83	9.2	0.58	6.4
• Ease of Modular Upgrading		1.0		1.0		1.0		1.0		0.5		0.5		0.5		1.0	
• Cost of Scarring for Growth		0.25		0.25		1.0		1.0		1.0		1.0		1.0		0.25	
• Integration with Growth Space Station		0.5		0.5		0.5		0.5		1.0		1.0		1.0		0.5	
• Operational Utility	10	0.48	4.8	0.44	4.4	0.48	4.8	0.31	3.1	0.76	7.6	0.48	4.8	0.38	3.8	0.31	3.1
• Launch Packaging/Keel Storage		0.9		0.0		0.9		0.0		0.55		0.93		0.27		0.48	
• Ease of Deployment		0.5		1.0		0.5		0.5		0.5		0.25		0.25		0.25	
• Refueling Mode		0.25		0.25		0.25		0.25		1.0		0.5		0.5		0.25	
• Ease of Repair/Restoration		0.25		0.5		0.25		0.5		1.0		0.25		0.5		0.25	
• Potential SSPE Integration	5	0.73	3.6	0.73	3.6	0.3	1.5	0.43	2.1	0.3	1.5	0.5	2.5	0.5	2.5	0.7	3.5
• Propulsion System Energy Requirement		0.95		0.7		0.35		0.35		0.1		0.5		0.5		0.9	
• Interaction With Other SS Subsystems		0.5		0.75		0.25		0.5		0.5		0.5		0.5		0.5	

Note: R = Rating and WR = Weighted Rating

As shown in Tables 15 and 16, the two H_2 systems had the highest reliability and safety rating (highest weighted criteria) since these systems were simple (one propellant) with the lowest number of components. Since only H_2 is discharged, these same two candidate systems had the lowest contamination potential and therefore the highest contamination potential rating. The lowest technical risk (highest technical risk rating) was achieved by the O_2/H_2 system, the warm H_2 system, and the combined H_2 attitude control system with O_2/H_2 reboost. The technology for these candidate systems are well in hand and system test results from the SSPS test bed will soon be available.

The O_2/H_2 water electrolysis system resulted in the highest IOC and LCC rating due to the greatly reduced operational costs. However, the warm H_2 system with H_2 resistojets also achieved a high IOC and LCC rating due to a combination of a low development cost and a low resupply cost (high delivered specific impulse of resistojets). Candidate systems with resistojets and O_2/H_2 water electrolysis are attractive from a growth potential standpoint due to lower resupply cost. Also, candidate system integrated with the Environmental Control and Life Support System (ECLSS) reduce growth station scarring and permit integration with other space station systems and therefore these systems had the highest growth potential ratings. From an operational utility standpoint, the O_2/H_2 water electrolysis candidate achieved the highest rating due to its repairability and simple water resupply. Due to their low energy requirements and their compatibility with platform propulsion requirements, the O_2/H_2 and the warm H_2 systems achieved the highest Space Station Program Element (SSPE) integration rating.

This analytical task resulted in many technical conclusions regarding the SSPS. These include the fact that accumulators enable the decoupling of the propellant tank pressurization and propellant thermal conditioning from the thruster operation. The lowest system and resupply weight and volume were achieved by the O_2/H_2 system. The addition of H_2 resistojets was extremely beneficial to the warm H_2 system in terms of significant reductions in system weight and volume. In addition, the utilization of

resistojets can provide the capability of high velocity propulsive disposal (free molecular flow) of ECLSS and on-board manufacturing processes waste products. Although an in-depth study of contingency propellant storage was not performed, ambient propellant storage would be preferred over cryogenic storage due to its simplicity. Ambient propellant storage would definitely be the preferred choice if the contingency total impulse was low; however, if the contingency total impulse requirements are high, cryogenic propellant storage may be required to reduce storage volume.

Based on customer needs, Orbit Transfer Vehicle (OTV) propellant depot (O_2 and H_2), ECLSS evolution, shuttle orbiter excess propellants, a fully integrated hydrogen, oxygen, and water economy can be envisioned for the space station. If this is accomplished, significant cost and operational benefits are possible. The SSPS, ECLSS, shuttle orbiter, and the station manufacturing facilities would be combined into a single system that would utilize common O_2/H_2 storage and waste water electrolysis facilities. Waste fluids from ECLSS and manufacturing facilities would be recycled to produce potable water, oxygen, and hydrogen for use by the station customers. The SSPS would have the flexibility to use water products that might not economically be recycled for use by station customers and balance the on-orbit supply of oxygen and hydrogen.

Overall, the results of this study clearly indicated that oxygen/hydrogen-based propulsion systems can provide simple, low cost, and viable systems for the IOC space station. Furthermore, these systems can eventually provide the basis for an oxygen, hydrogen, and water economy for a fully integrated space station.

TASK II - TEST BED DESIGN AND FABRICATION

The system design goal was to provide a test bed representative of a space station propulsion system capable of demonstrating the readiness of oxygen/hydrogen propulsion technology for the IOC space station application. In addition, the system must be flexible enough to evaluate various supply concepts and components for use on the IOC and the growth stations.

To accomplish these goals, the test bed was designed as a modular system with oxygen and hydrogen accumulator tanks, a resistojet propulsion module, and a 25-pound thrust engine module mounted in a 9-foot cube structure to simulate the basic building block structural element of the space station (Figure 21 and 22). Various types of fluid supply modules can be connected to the propulsion module in order to simulate a complete system. A supercritical gas storage tank system was designed for the test bed (Figure 23), however, due to the rapid progress of the electrolysis system, it has been delayed; an electrolysis module will be installed and tested in the near future. The flexibility of the test bed easily accommodated this early change.

The test bed was designed for testing in MSFC Test Cell 302 at an operating pressure of 1 torr (Figure 24). Valve and control components were selected from standard commercial equipment to provide simulation of flight hardware without the expense and time required to obtain flight components and with the belief that little would be lost to the technology demonstrations. Updating to flight type equipment can be accomplished on a component by component basis as truly representative hardware is defined and made available. All line assemblies were fabricated of welded tubing with Cajon-VCR fittings used on all removable joints and components to accommodate the low vacuum pressures. A schematic of the hydrogen system is shown in Figure 25. The oxygen side is similar with the exception of the resistojet plumbing, which does not exist on the oxygen side. Tables 17 and 18 summarized the components used.

The oxygen and hydrogen components are separated and mounted on two panels beneath the tanks on opposite sides of the cube. A third panel mounted in the center of the cube contains the resistojets and engine module components.

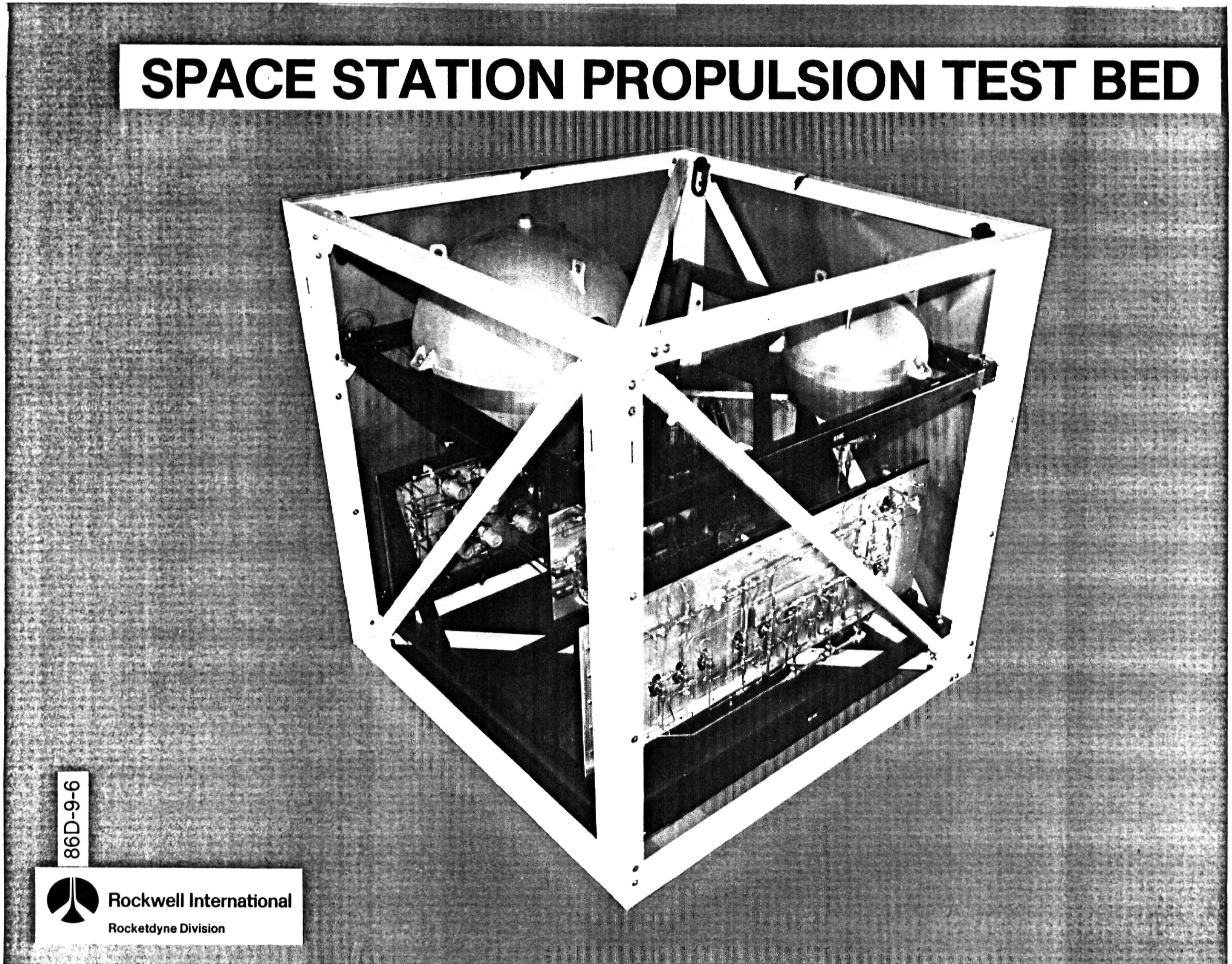

Figure 21. Test Bed Assembly

PRELIMINARY FLIGHT SYSTEM-TO-TEST BED DESIGN

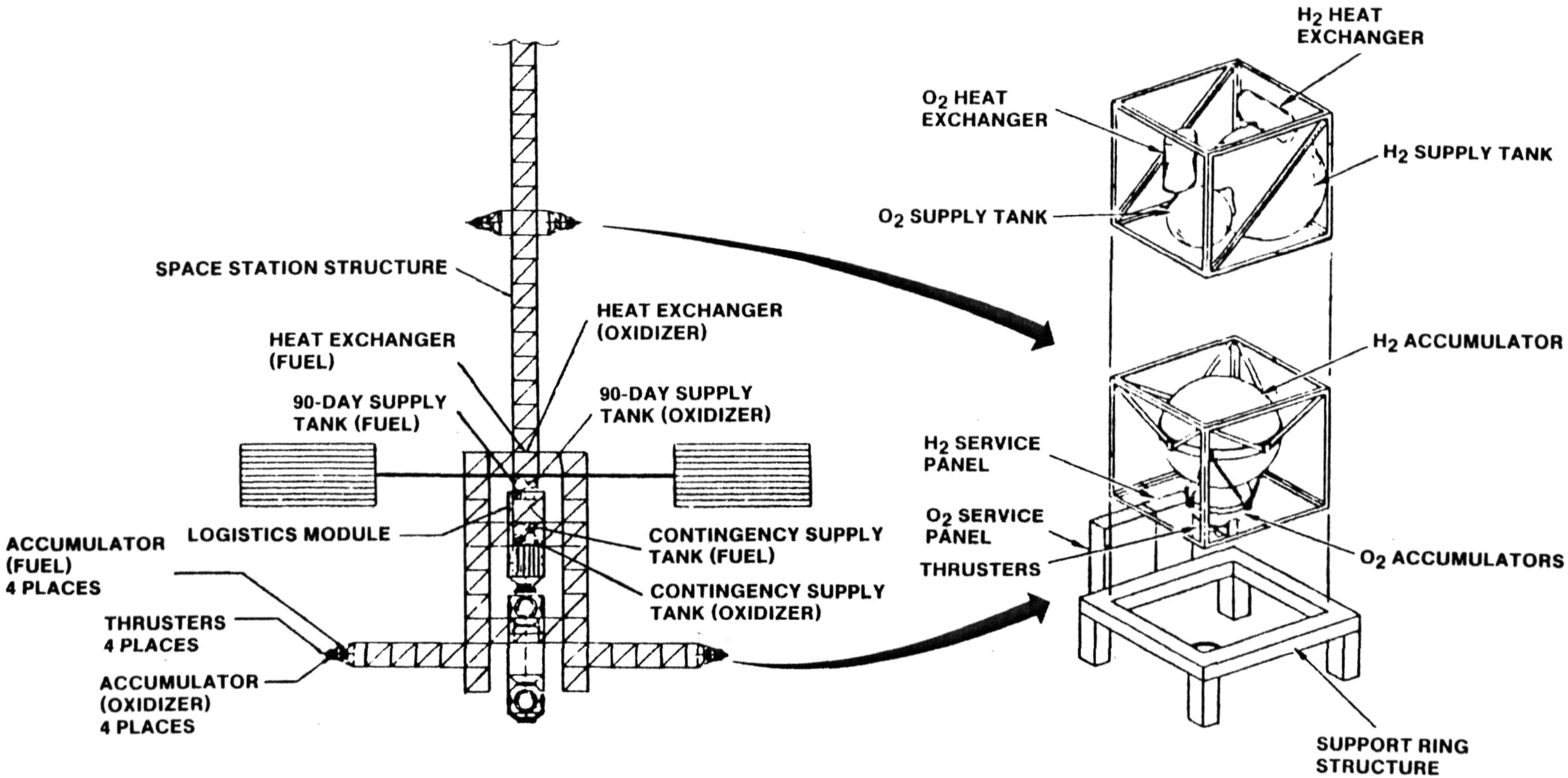

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Figure 22

SSPS TEST BED GROWTH EVOLUTION

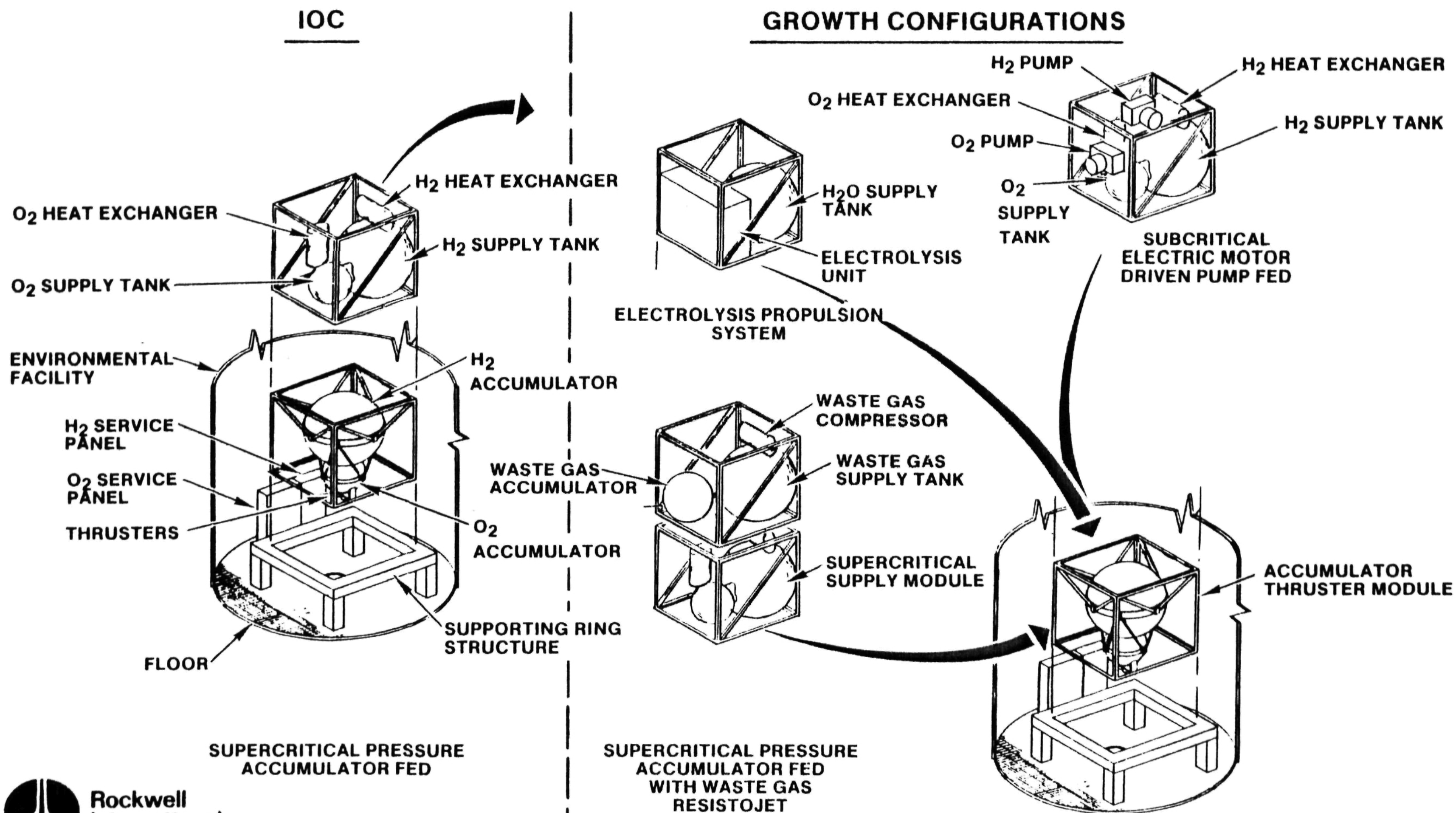

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Figure 23

SPACE STATION O/H_2 PROPULSION TEST BED

TEST POSITION 302 VACUUM CHAMBER VERTICAL INSTALLATION

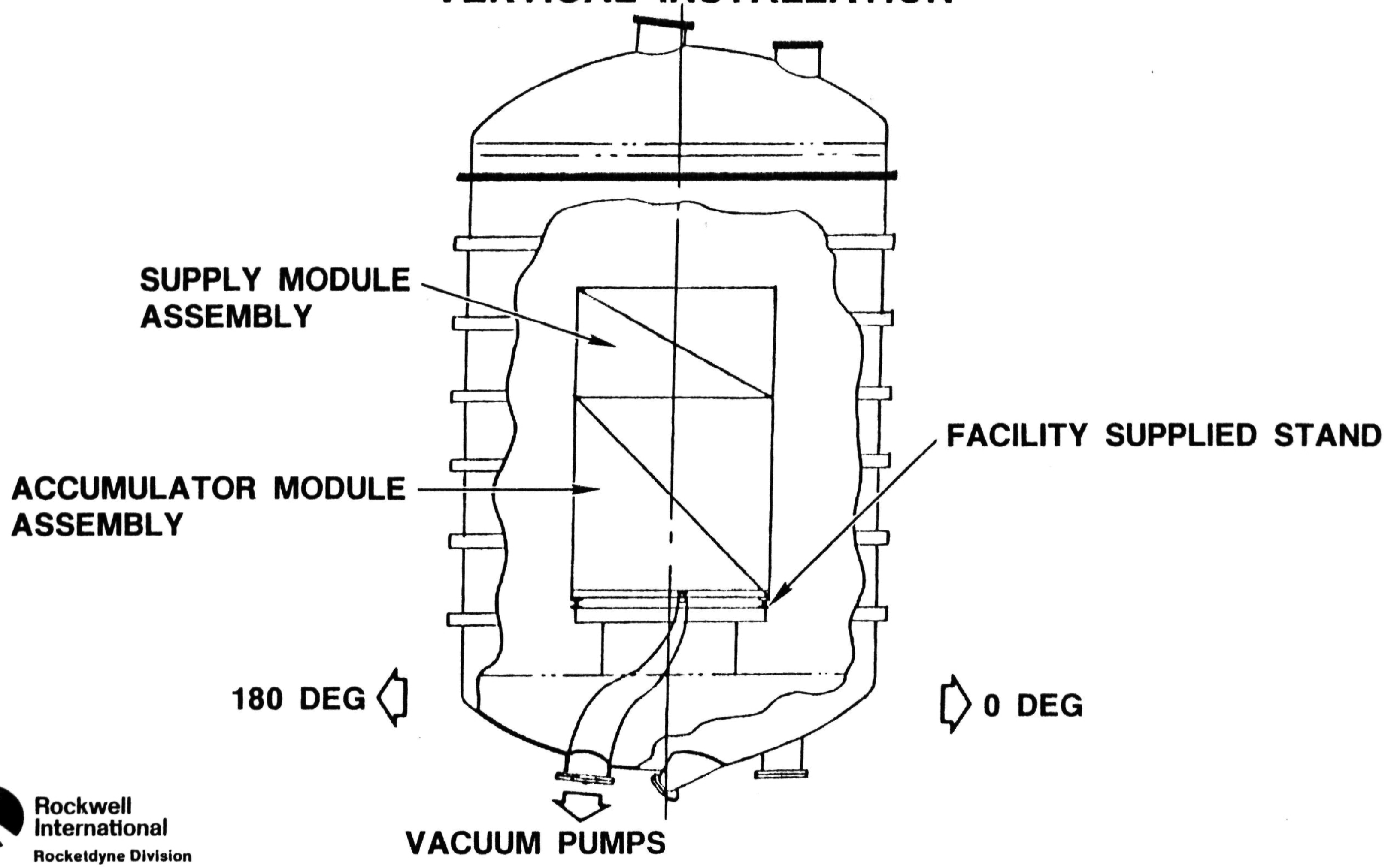
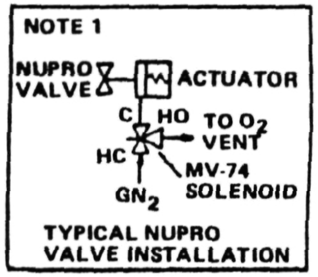
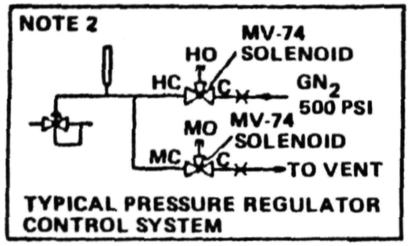


Figure 24

HYDROGEN SYSTEM SCHEMATIC





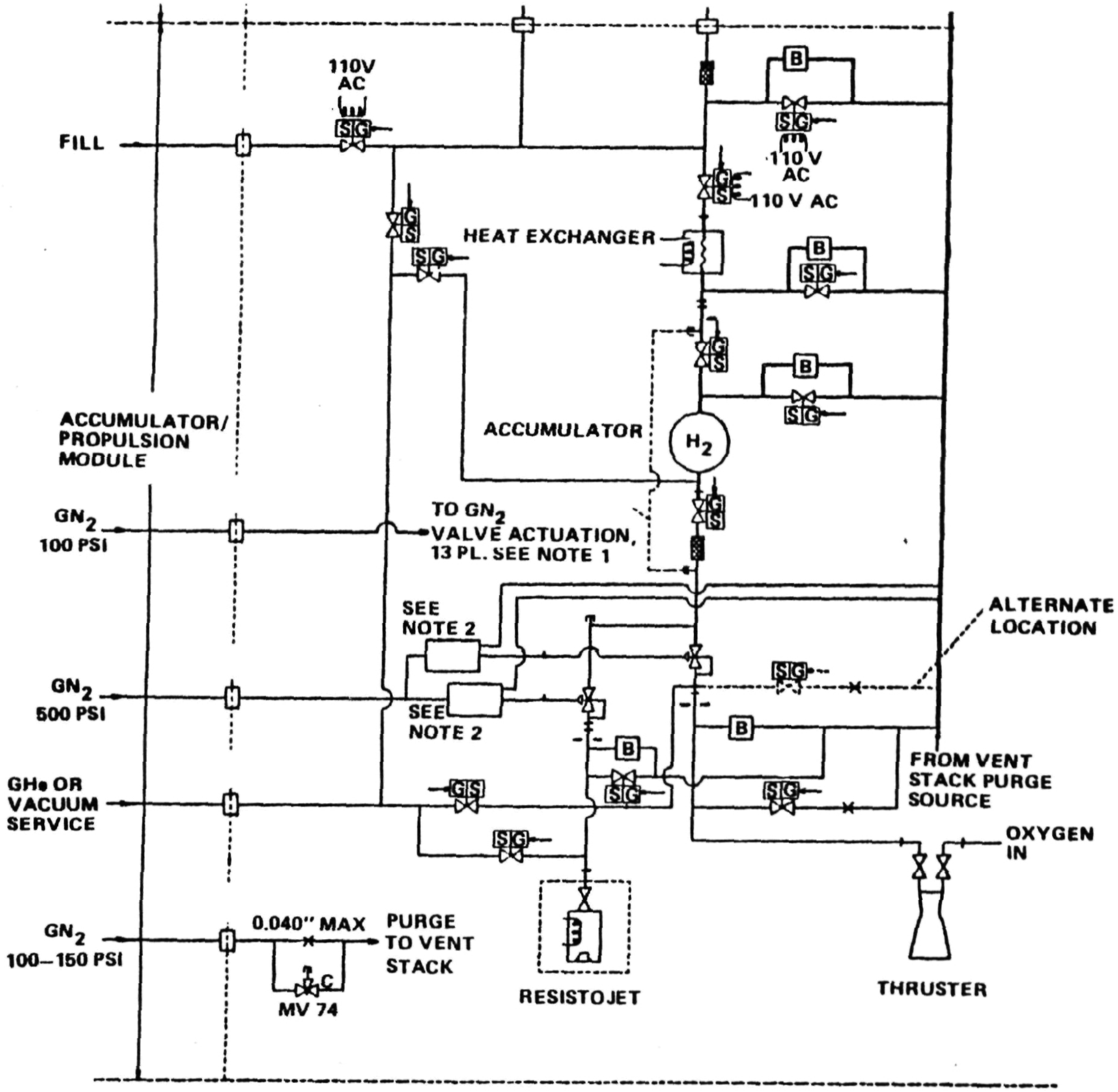


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Figure 25

Table 17 Component Operating Ranges

	Test Bed Subsystem Operating Ranges					
	Pressure, psig			Temperature, R		
	Nom	Max	Min	Nom	Max	Min
Accumulator						
Oxygen	1000	1600	200	400	600	300
Hydrogen	750	1300	200	300	600	200
Thruster Module						
Oxygen	145	250	100	530	600	395
Hydrogen	190	250	100	530	600	395
Gaseous Nitrogen Valve Actuators	125	220	100	530	600	500
Vacuum Service	--	--	1 torr	530	--	--
Gaseous Nitrogen Regulators	500	500	0	530	--	--

Table 18 Component Summary

Valves

- Nupro "U" series bellows value
- Pneumatic operator - electrical heater
- Body - 316 stainless steel
- Bellows - 347 stainess steel
- Seat insert - Kel-F (batch tested for oxygen) alternate - stellite

Filters

- Vacco industries
- In-line filter
- Disc type
- Viking filter - modified fittings
- All metal - 304-L (oxygen), 316-L (hydrogen)

Lines

- 321 stainless steel seamless tubing

Fittings

- Cajon-VCR
- 316 and 316-L stainless steel
- Gaskets - silver plated 316

Accumulator Tanks

- ASME coded vessel
- Oxygen - 304-L stainless steel
- Hydrogen - 316-L stainless steel
- Grayloc closeout flanges

Regulators

- Grove model 94
- Batch tested soft goods for oxygen

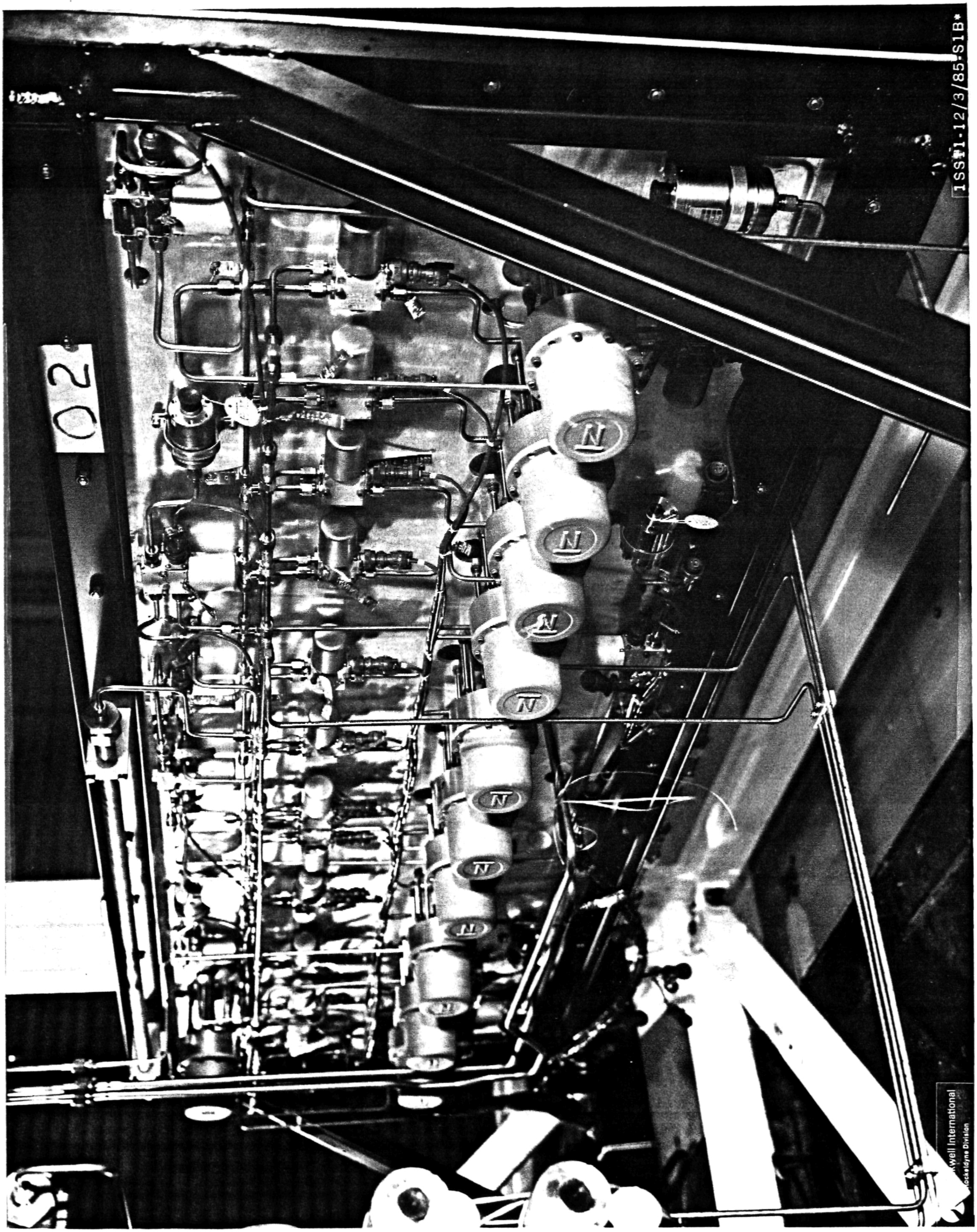
The components and plumbing were mounted to provide easy access for repair or replacement with flight-type components as available (Figure 26).

The accumulator tanks are standard ASME coded vessels with a 4-to-1 safety factor fabricated by Capital Westward Company for the test bed. The tank contains sufficient propellants for approximately 830 seconds of engine firing time (20,800 lb-sec); but due to the temperature drop, a single long duration burn is limited to about 600 seconds (Figure 27). The effect of the temperature change is to cause a slow increase in thrust with a slight change in mixture ratio to the point that the sonic venturies unchoke. Figure 28 shows this effect for a mixture ratio 4 run condition although the same effect occurs at all mixture ratios. To prevent these variations, mass flowrate control has been incorporated into the control system.
The system was provided with sufficient instrumentation to ensure safe operations as well as obtain diagnostic data. All transducer systems were designed to be compatible with existing MSFC standards, and the pressure transducers were supplied by MSFC.

In keeping with the concept of supplying MSFC with a complete stand alone test bed, an integrated control and data acquisition system was included. The design goals specified a system that would exercise overall control of test bed operations with a maximum amount of automation, demonstrated safety, and high reliability. Test Bed operation will then be similar to that required on the Space Station, but with a high degree of flexibility necessary for a test development program. Computer control systems with these characteristics have been used at the Rocketdyne Santa Susana Field Laboratory (SSFL) for over 10 years, and it was decided to use the basic concepts and techniques developed for them as a design basis for the test bed system.

The systems centered around minicomputers and associated components, acquire engineering data while controlling valves, monitoring parameter limits and events, and completely controlling the test sequence. To do these

Figure 26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RUN TANK PRESSURE vs TIME

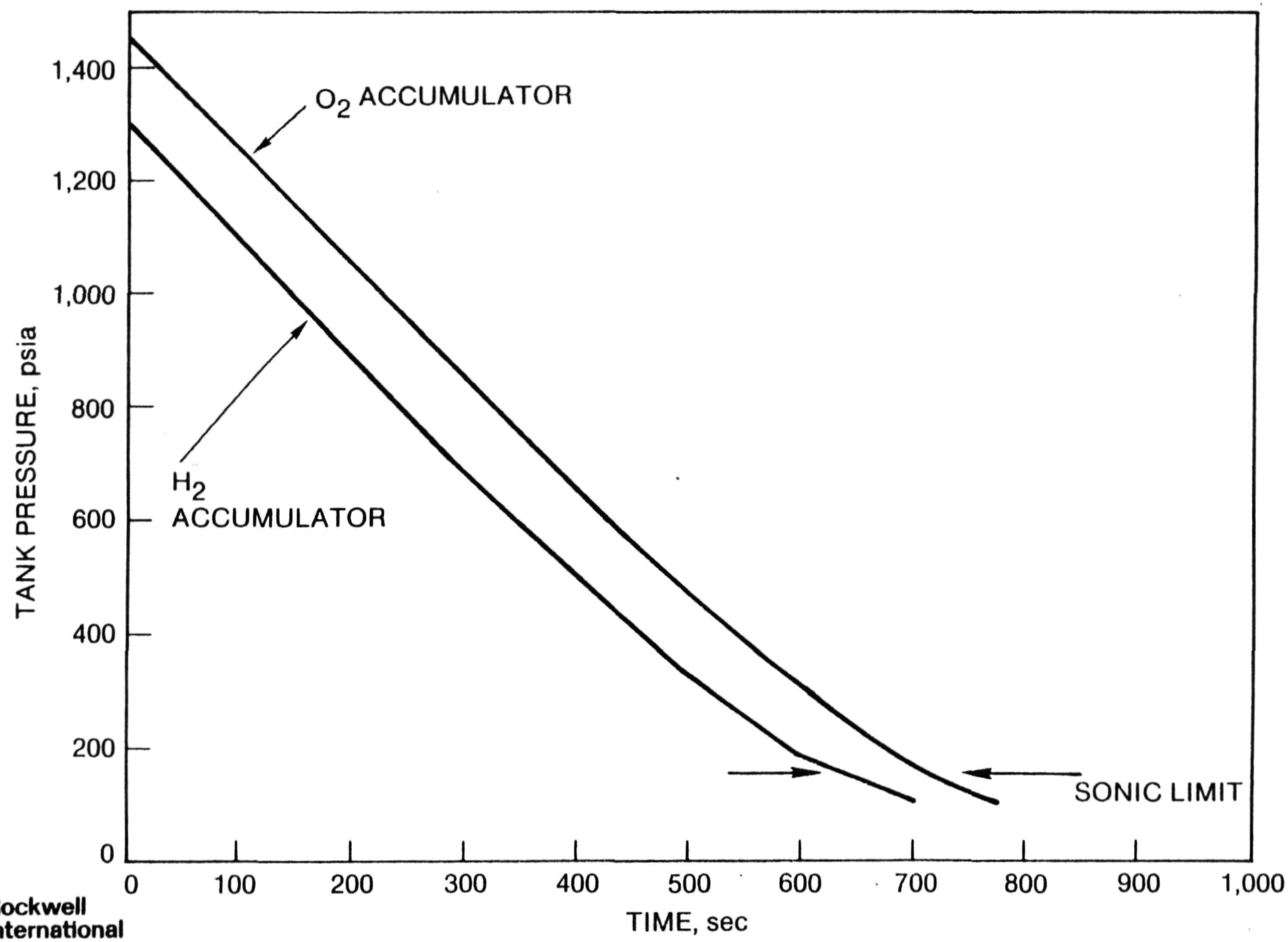

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Figure 27

CHAMBER PRESSURE AND MIXTURE RATIO vs TIME

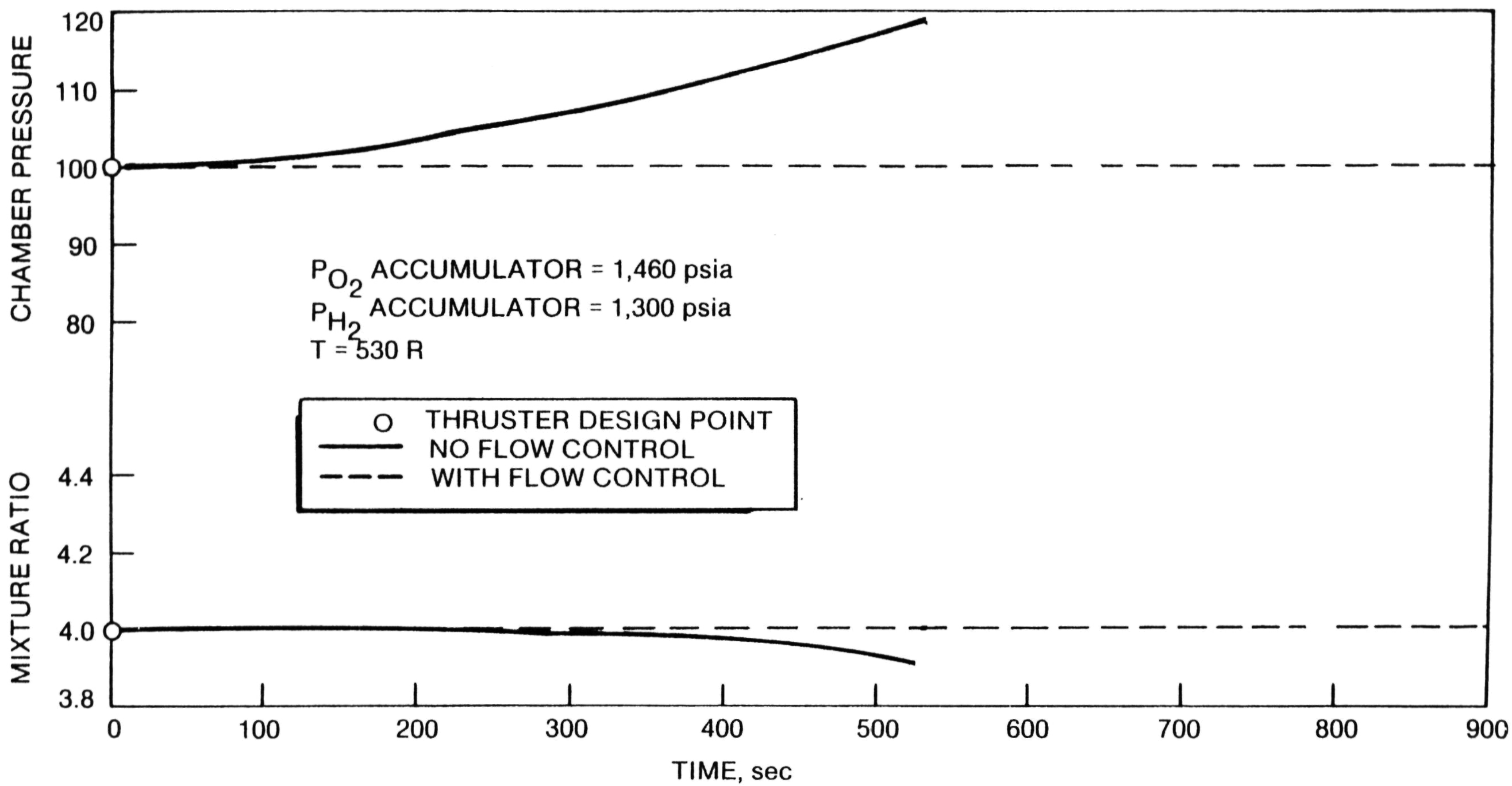

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Figure 28

integrated operations, specialized software was written including a high order computer language called Rocketdyne Test Control Language (RTCL). The software system and concepts were also implemented in the SNIA BPD test facility in Colleferro, Italy in 1981, and at the Air Force Weapons Laboratory in 1982.

In recent years, many of the test facilities at SSFL have had the RTCL software implemented in Data General computer hardware; and this led to the selection of a Data General Desktop Model 30 as the microprocessor utilized for the test bed.

The control system is composed of a manual control panel, the microprocessor, and its various ancillary components and signal conditioning equipment (Figure 29 and Table 19). All of the components are assembled into a compact desk arrangement (Figure 30), which is located in the control center about 500 feet from the test cell.

When power is initially applied, control of all devices is from the manual panel. When automatic control is desired, a momentary switch shifts power to the computer. Control remains with the computer until a reset circuit is actuated either manually or from the "watchdog timer."

The "watchdog" is a Rocketdyne built device that monitors timing signals from three of the primary programs in the control software. If any of the programs fails to signal within a set cycle time, control automatically returns to the manual panel. In this way, failure of the computer system can be detected; and by means of presetting manual switches, the test bed can be returned to a safe condition.

A block diagram of the system is shown in Figure 31.

COMPUTER CONTROL SYSTEM BLOCK DIAGRAM

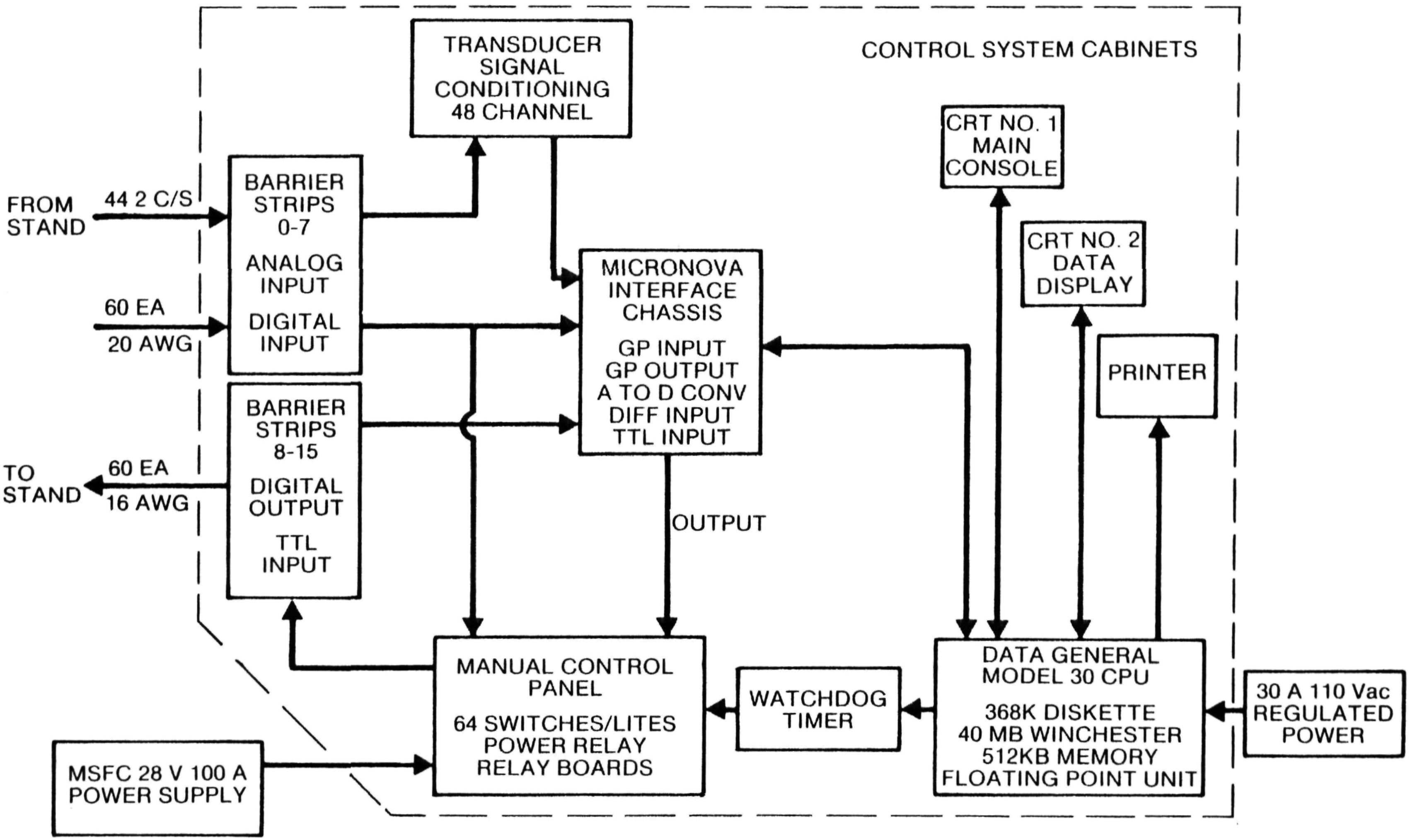

Figure 29

Table 19 Microprocessor Hardware Configuration

Microprocessor is a Data General Desktop Model 30 with the following features ● 512 kilobyte semiconductor memory with byte parity ● Hardware floating point unit ● 368 kilobyte diskette unit ● 40 megabyte winchester hard disk ● Two 123-watt power supplies ● Digital-to-analog converter ● Differential mux ● 64 digital 28 Vdc outputs (optoisolated) ● 64 digital inputs (optoisolated) ● Printer ● CRT display for 24 channels of engineering unit data ● CRT terminal for operator interface

TEST BED CONTROL SYSTEM

86D-9-1413

Figure30

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OF POOR QUALITY

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CONTROL SYSTEM BLOCK DIAGRAM

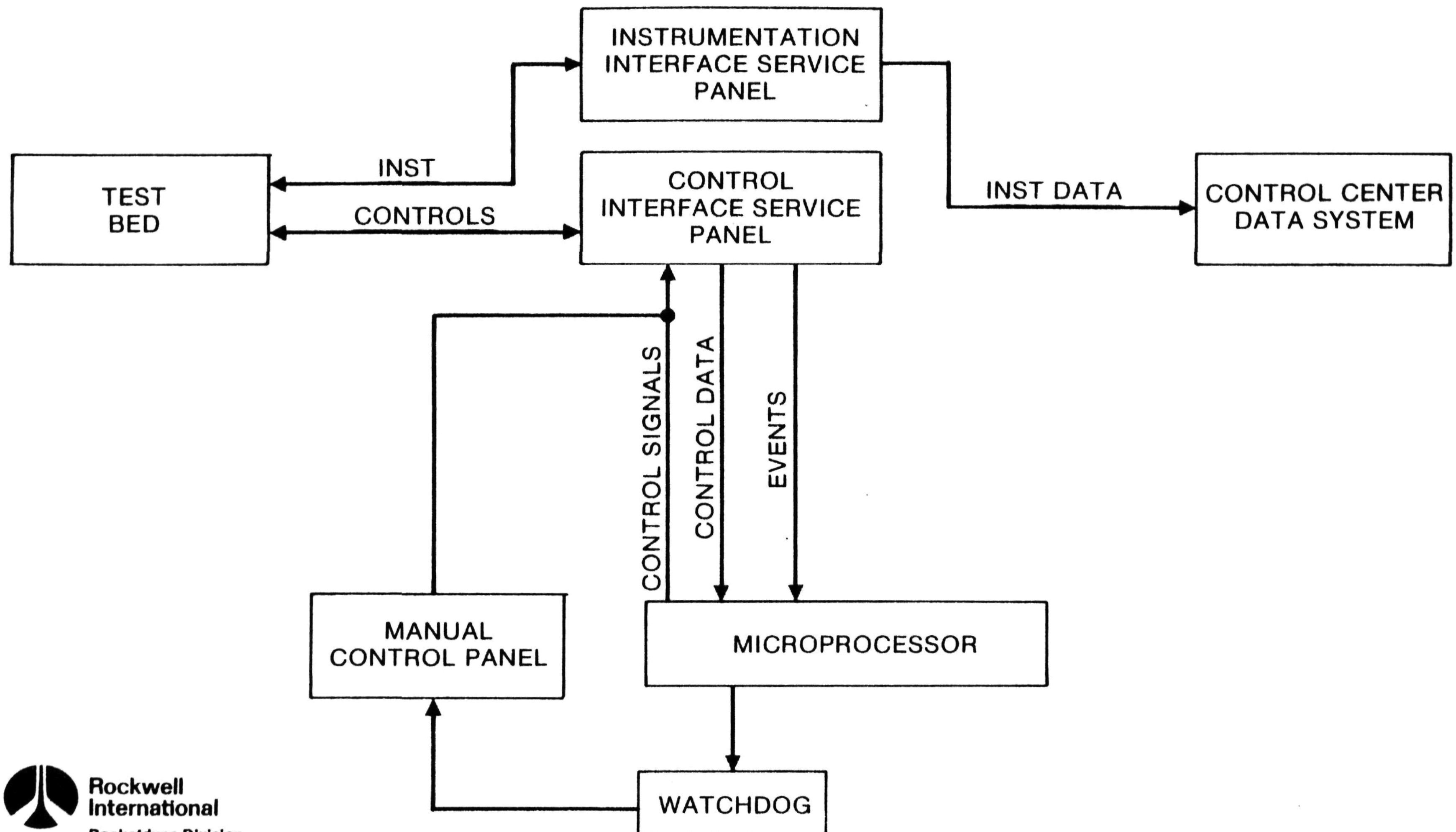

Figure 31

The Rocketdyne test control langugage implemented in the Test Bed is a very flexible and powerful high order programming language consisting of 38 basic commands with up to 4 variables associated with each. Table 20 describes the primary features.

The event data are recorded on the hard disk every 20 milliseconds and the parameter data are recorded every 100 milliseconds. Off-line programs are available to reduce the data to engineering units and to produce a time line of all of the events that occurred.

The mass flowrate of the main propellants can be calculated by using pressure and temperature upstream of a sonic venturi and can be controlled by comparing the calculated values to desired values and making necessary pressure corrections. Initially, the pressure upstream of the venturis is controlled by simple regulators. The reference pressures of the regulators is controlled by the computer to maintain the flowrate between upper and lower limits. Future plans call for replacement of the regulator with computer controlled throttle values to maintain very precise flowrates.

To connect the control system to the test bed, an interface box is used. All control transducers and valves on the bed are wired to this interface box. Because MSFC maintains strict separation of control and data acquisition functions, a second interface box was provided for the diagnostic data.

Excess capacity was provided in both interface boxes to allow for changes or future growth (Table 21). Marshall Space Flight Center personnel wired from terminals strips in the two boxes, through bulkhead connectors in the cell wall, and from there to the control center and recording center (Figure 32). The diagnostic data signals are conditioned and digitized in the test cell area prior to being tansmitted approximately 1000 feet to the recording center. Digital displays of engineering unit data are provided in the control center during a test, and printouts of engineering unit data and plots of data can be produced shortly after completion of a test.

Table 20 RTCL Features

• Monitors 64 valve positions every 100 msec
• Controls sequence of 64 output signals on 1 msec basis
• Monitors 128 limits on raw or calculated data each 100 msec
• Performs corrective action or terminates for limits
• Uses flags, counters, and other branch statements for flexible sequence
• Emulates "expert systems"

Table 21 Instrumentation/Controls Capacities

Number of Parameters	System Capacity	Growth Available
13 diagnostic pressures	30	17
24 diagnostic temperatures	41	17
12 control pressures	20	8
7 control temperatures	24	17

DESIGN OVERVIEW INTERFACES

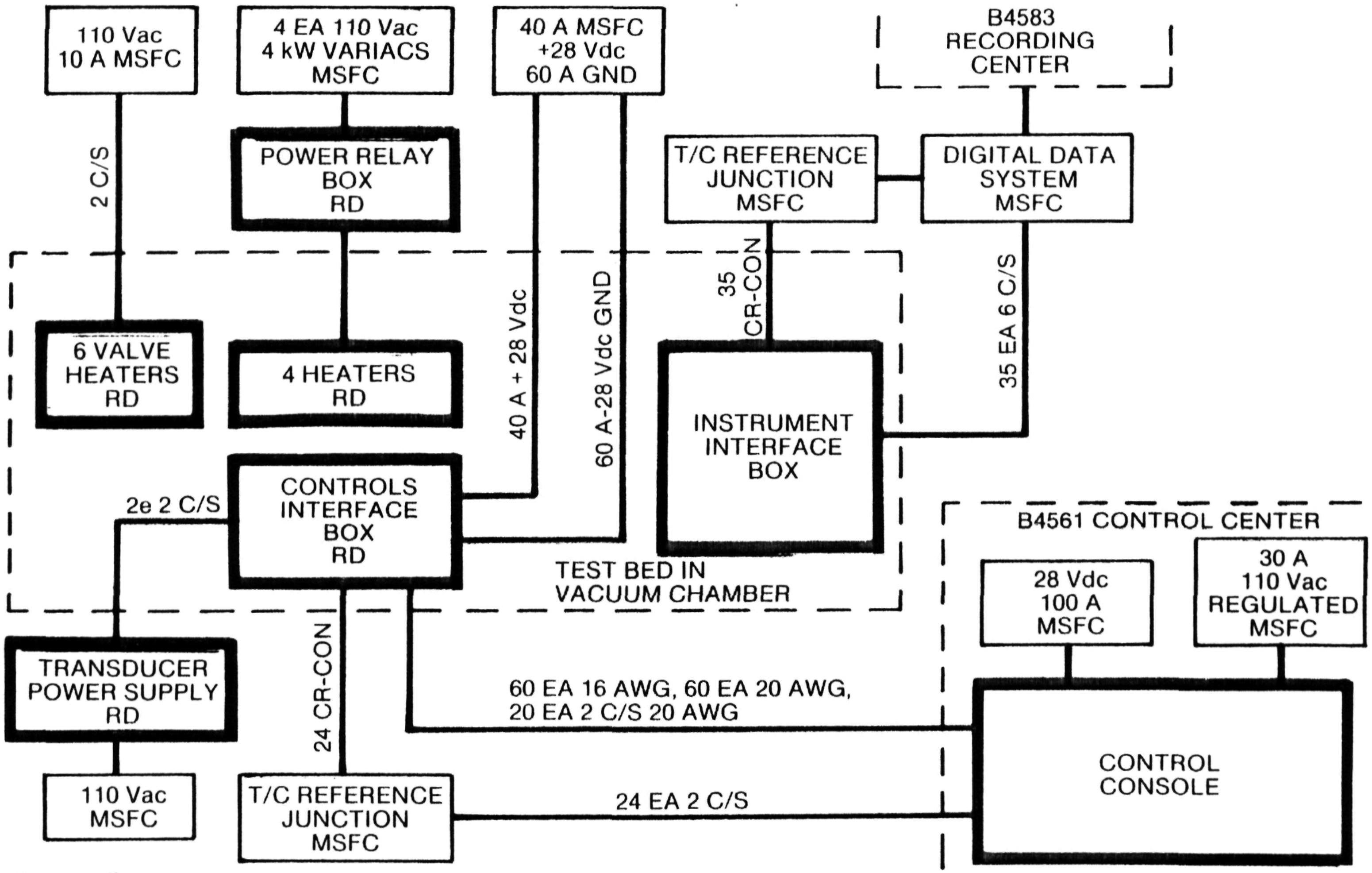

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Figure 32

TASK III MAJOR COMPONENT PREPARATION AND INTEGRATION

In early 1986 the availability of thrusters for use with the test bed at the high (MR = 8:1) mixture ratio needed for water electrolysis became a critical issue. To demonstrate the feasibility of operation at this level, funding was added to modify a thruster that Rocketdyne had supplied to NASA-MSFC for testing at mixture ratio 4:1. A redesigned injector was added to the existing thrust chamber (Fig 33 and 34), which had already been fired for over 12 hours.

The thruster was supplied to MSFC in April 1986 and a test series was carried out in test stand A-300 by MSFC personnel with Rocketdyne support present. A summary of the testing is presented in Tables 22 and 23.

To illustrate the capability of the thruster to work with the test bed or flight system, a mixture ratio excursion was conducted (Fig 35). Pressure response during this test is shown in Fig 36 and thermal performance in Fig 35 through 40.

Based on the results of these tests, the thruster, with slight additonal preparation is ready for integration into the test bed.

TASK IV - TEST SUPPORT

Due to funding limitations, effort on this task was limited to an initial meeting upon delivery of the test bed and support during thruster testing.

TECHNICAL PROBLEMS

NONE

PROTOTYPE 25 lbf GO_2/GH_2 THRUSTER FOR OPERATION AT MIXTURE RATIO = 8

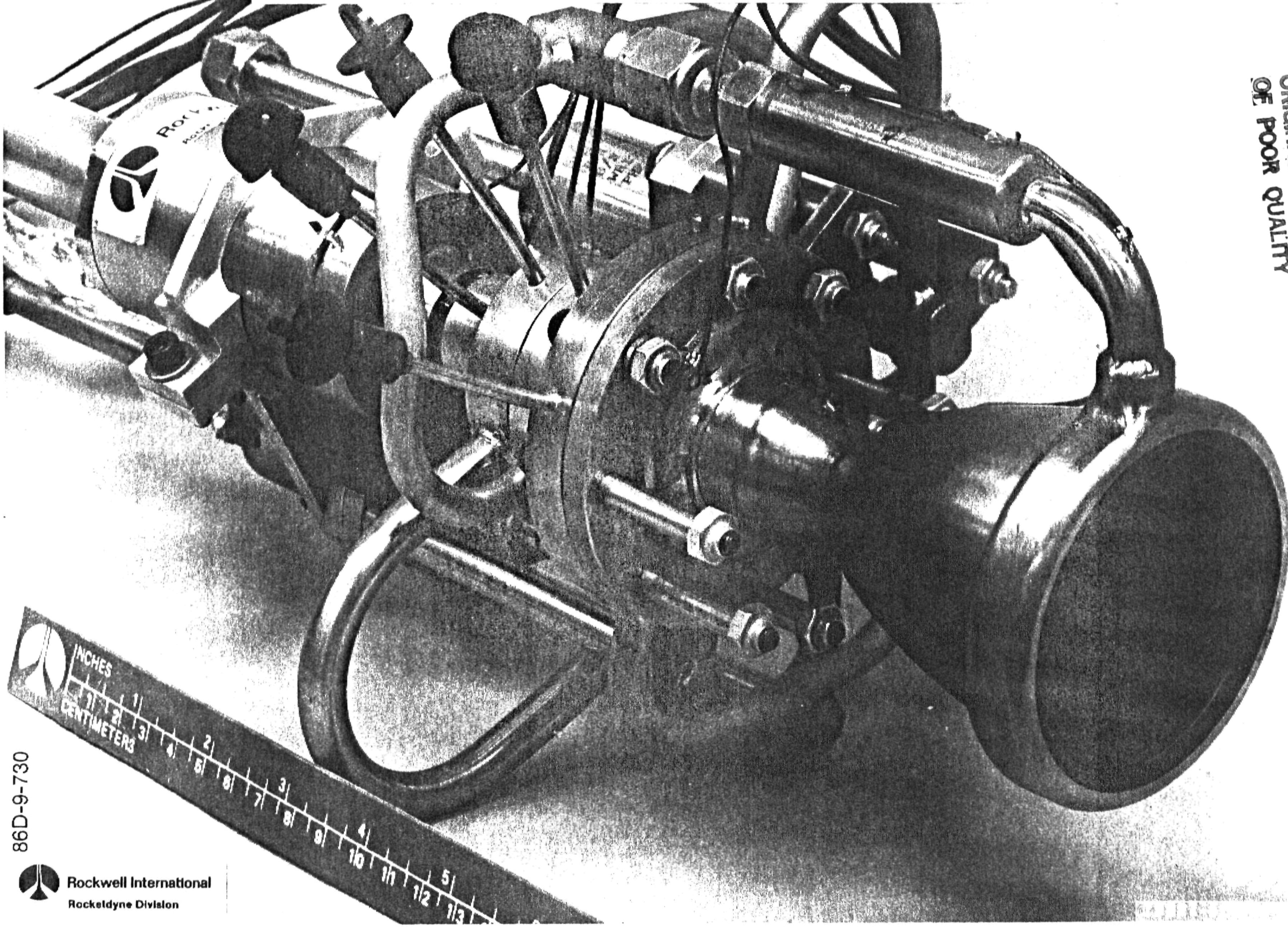

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Figure 33

PROTOTYPE 25 lbf GO_2/GH_2 THRUSTER INSTRUMENTATION LOCATION FOR HIGH MIXTURE RATIO OPERATION

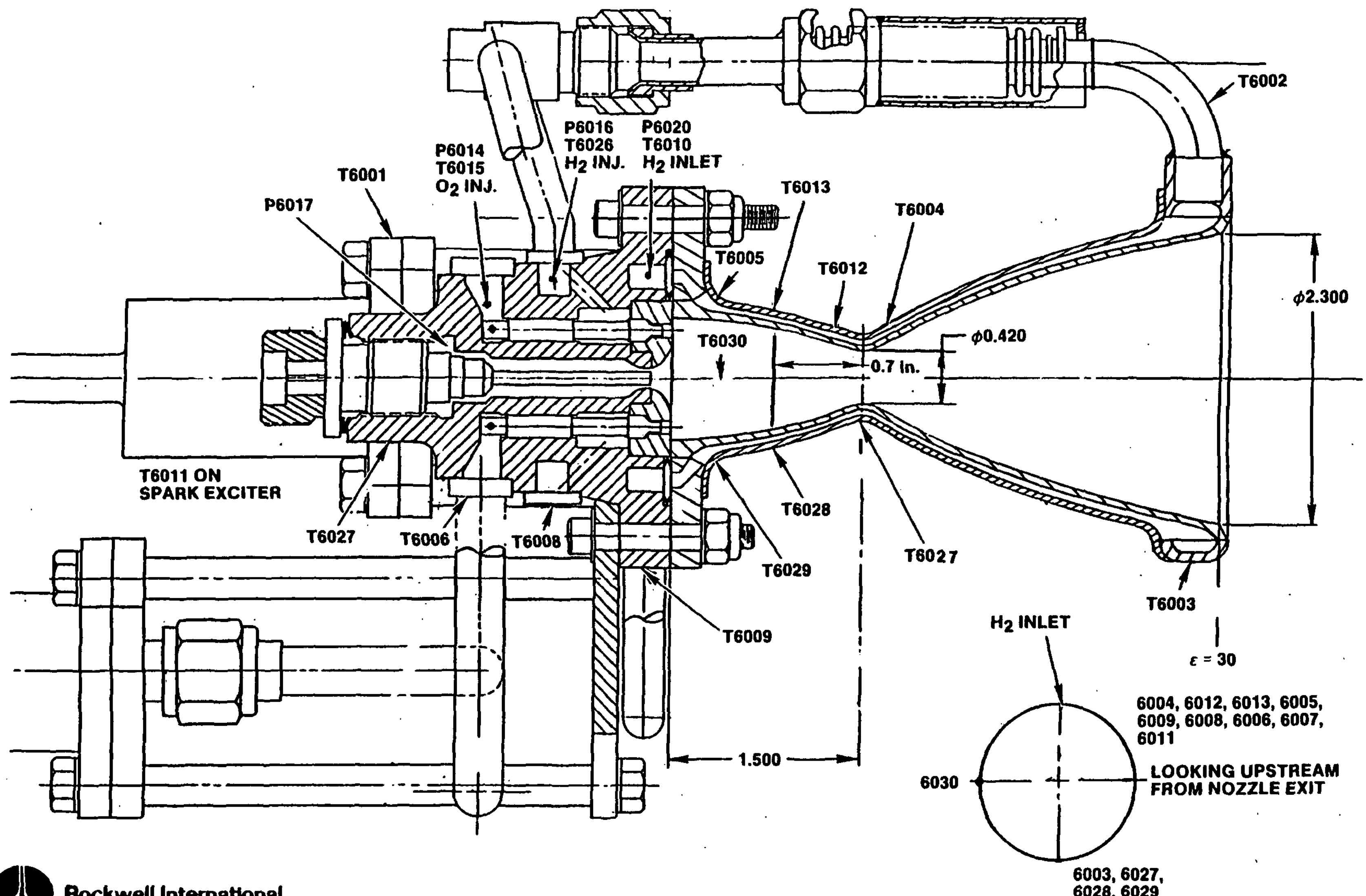

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Figure 34

PROTOTYPE 25 lbf GO_2/GH_2 THRUSTER TEST SUMMARY (MR = 8)

TEST FACILITY	NASA MSFC TEST STAND 300 VACUUM TEST CELL
THRUSTER CONFIGURATION	COAXIAL INJECTOR WITH COPPER FACE, DOWN-PASS COOLING OF THRUST CHAMBER, 40% BLC
ACCUMULATED RUN DURATION (h)	11.5
TOTAL IMPUSE AT MR = 8 (lb-s)	1.0 MILLION
MAXIMUM RUN DURATION AT MR = 8 (h)	6.1
TOTAL RUN DURATION AT MR = 8 (h)	11.1
MIXTURE RATIO RANGE	TRAVERSED FROM 7.9 TO 5.1 DURING 1500 s TEST
C* EFFICIENCY AT MR = 8 (%)	91
ESTIMATED VACUUM I_{sp} AT MR = 8 (ε = 30) (s)	360
THRUST (CALC) AT MR = 8 (ε = 30) (lbf)	27
CONDITION OF HARDWARE FOLLOWING TESTS	EXCELLENT

86D-9-732

Table 22

HIGH MIXTURE RATIO TEST SUMMARY

TEST NUMBER	TEST DATE	MIXTURE RATIO	TEST DURATION (s)
P102-155	4-21-86	8	2
156		8	10
157		8	22
158	4-22-86	7.8	10
159		8.1	30
161		7.9	60
162		8.1	600
163		8.0	12,640
164	4-23-86	7.9-5.1	1,500
165		8.2	4,500
166		8.0	22,000
		TOTAL	41,374

86D-9-733

Table 23

TEST NO.P102 0164 ** 4 /23 /86 113: 10: 7: 23.164

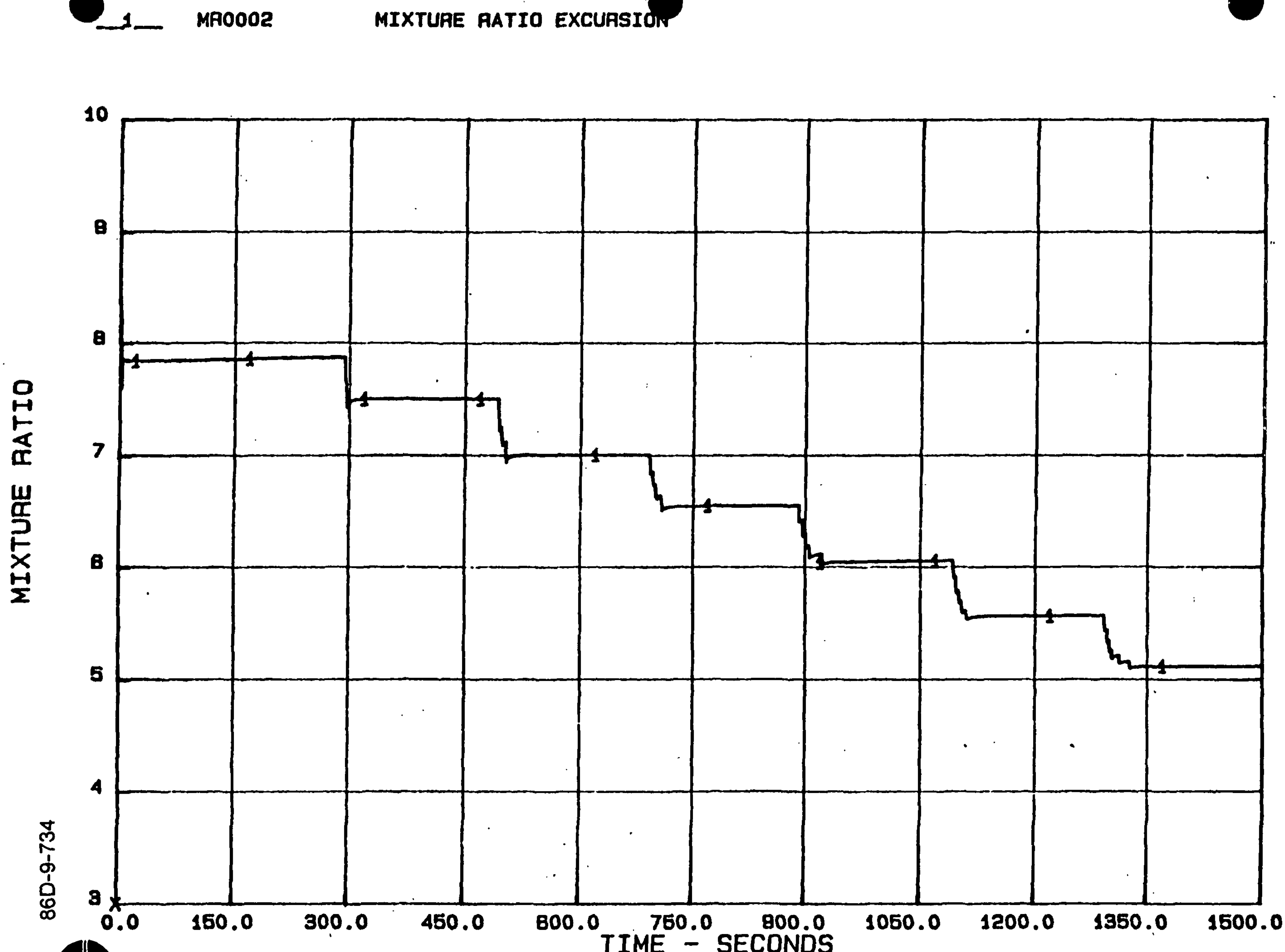

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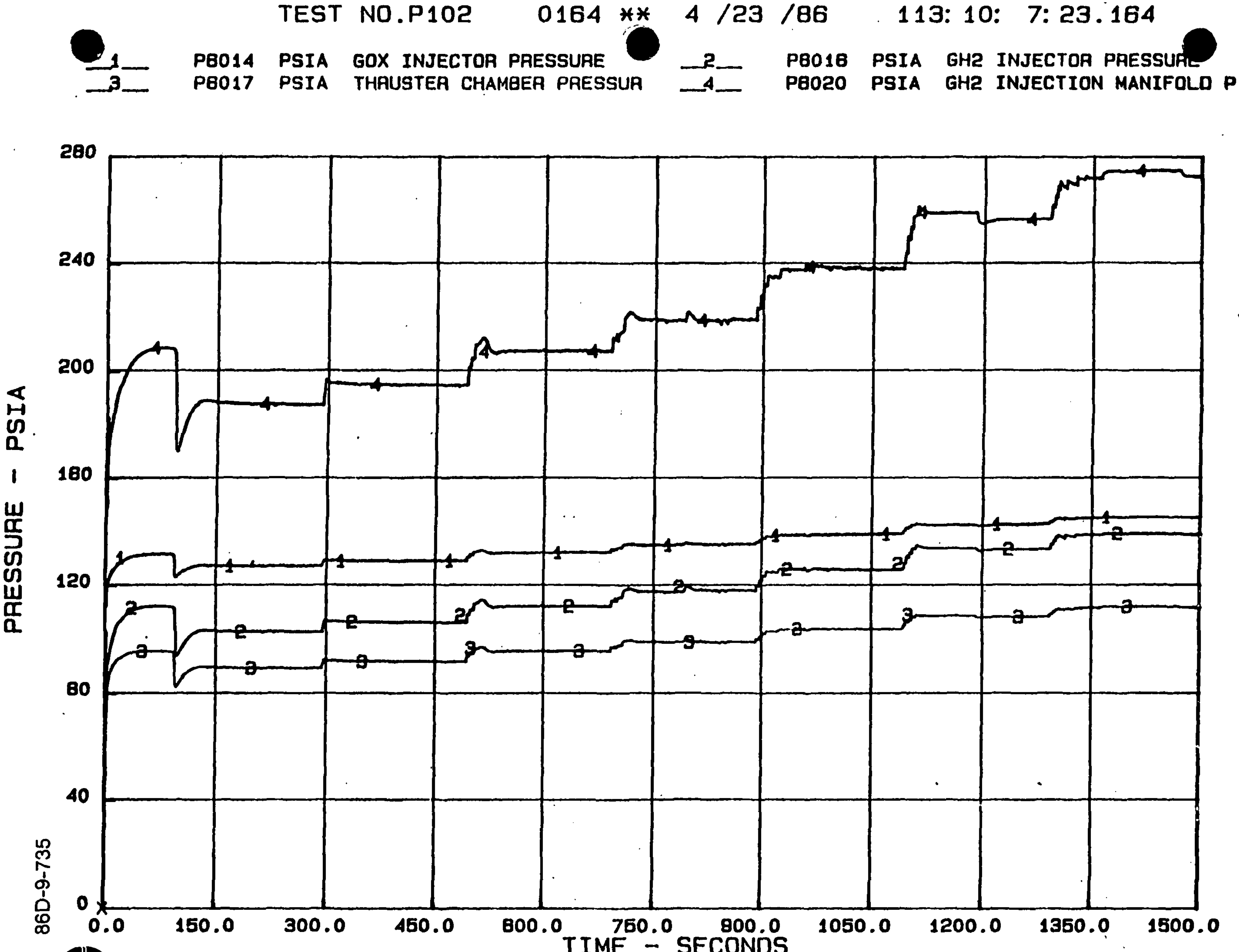
Figure 35



86D-9-735

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Figure 36

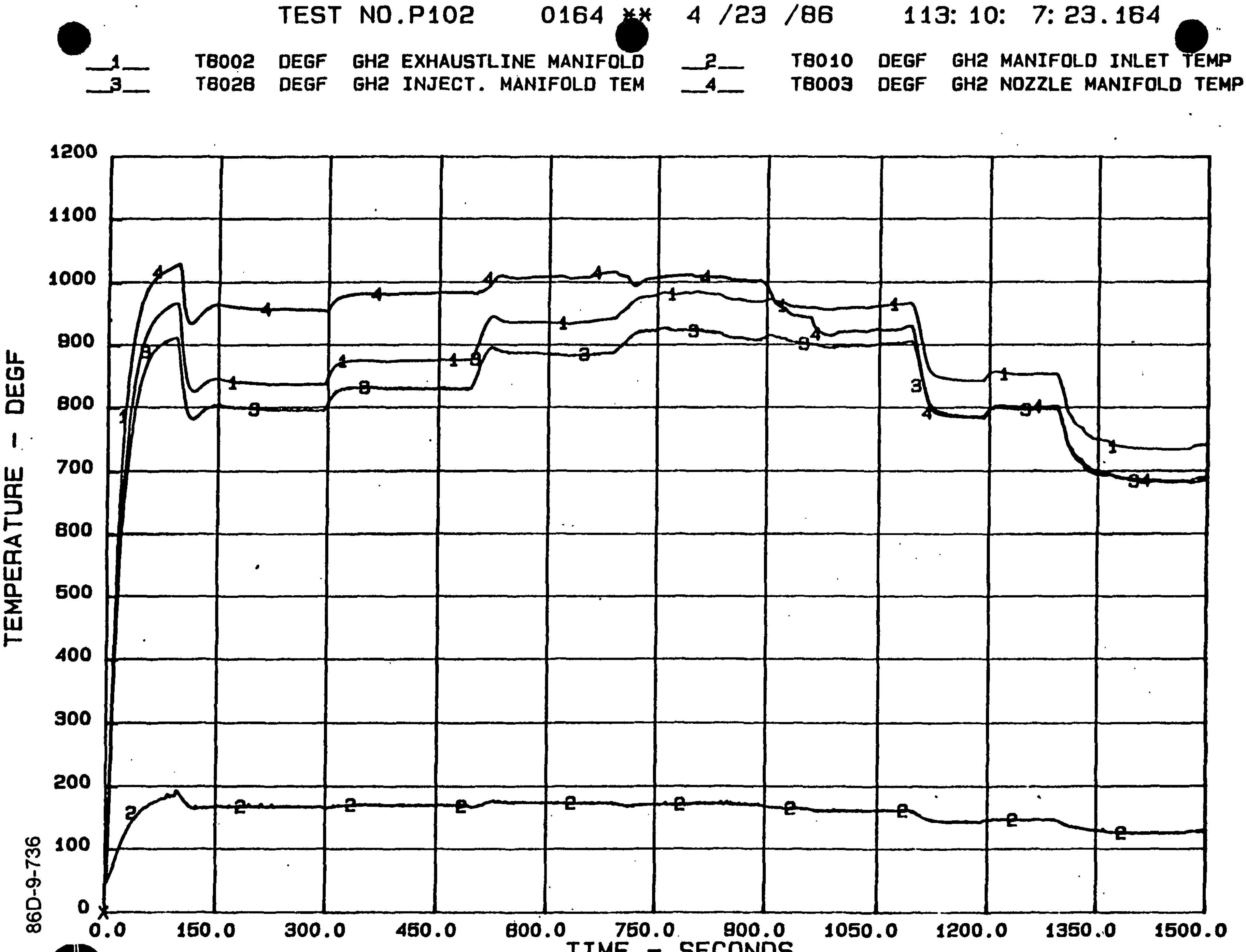

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Figure 37

TEST NO.P102 0164 ** 4 /23 /86 113: 10: 7: 23.164

__1__ T8004 DEGF THROAT OUTER WALL TEMP __2__ T8012 DEGF THROAT OUTER WALL TEMP
__3__ T8027 DEGF THROAT OUTER WALL TEMP

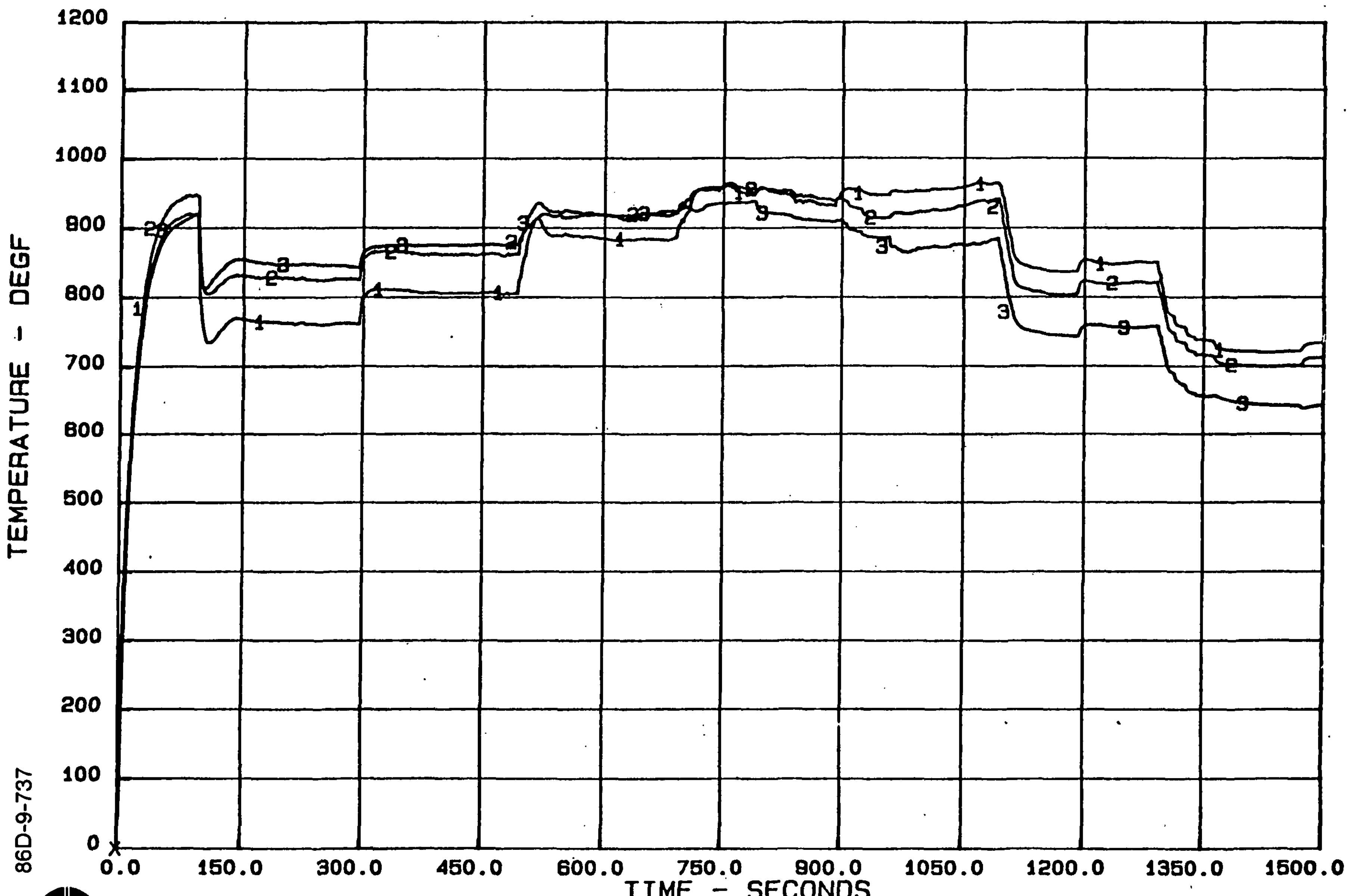

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Figure 38

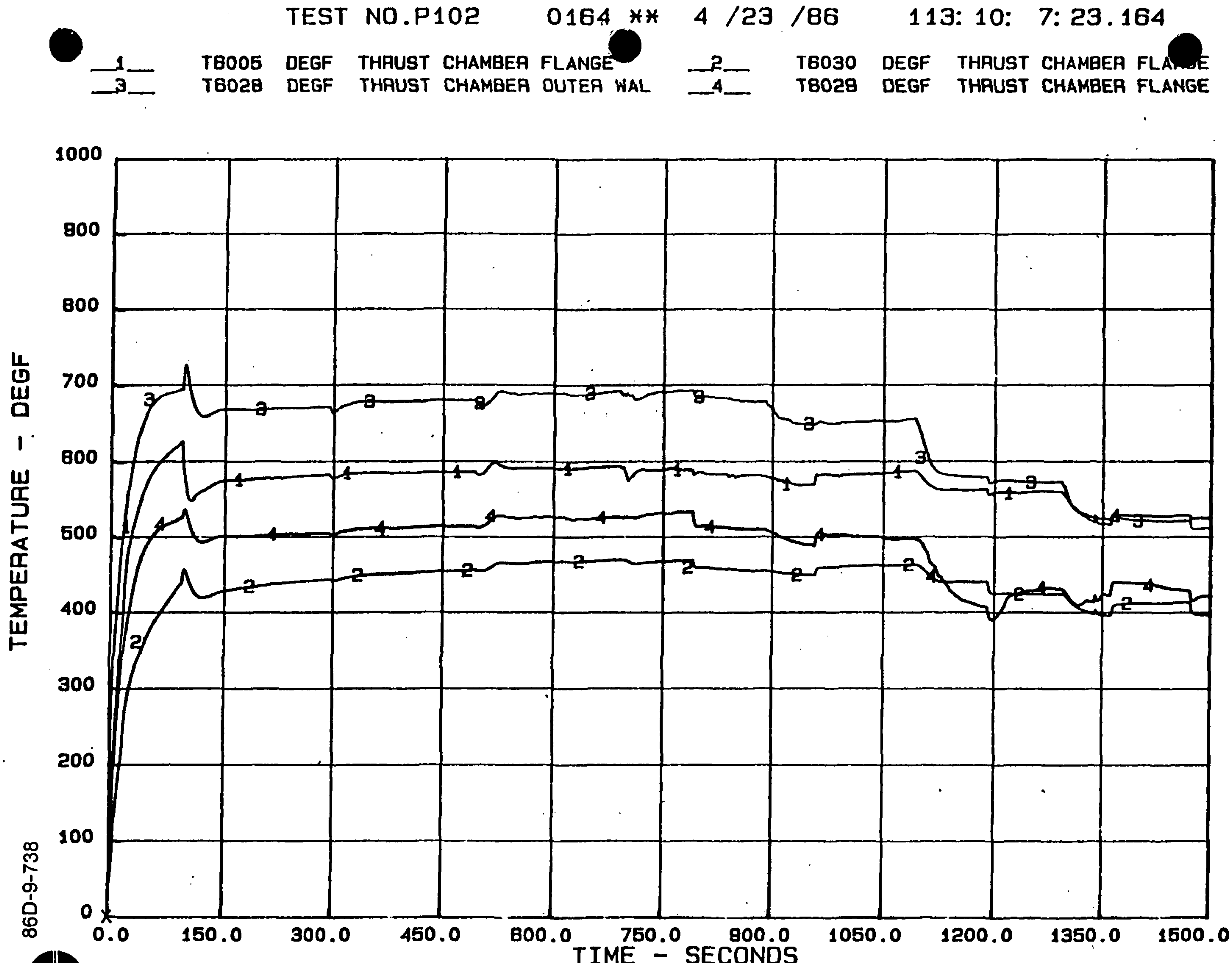

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Figure 39

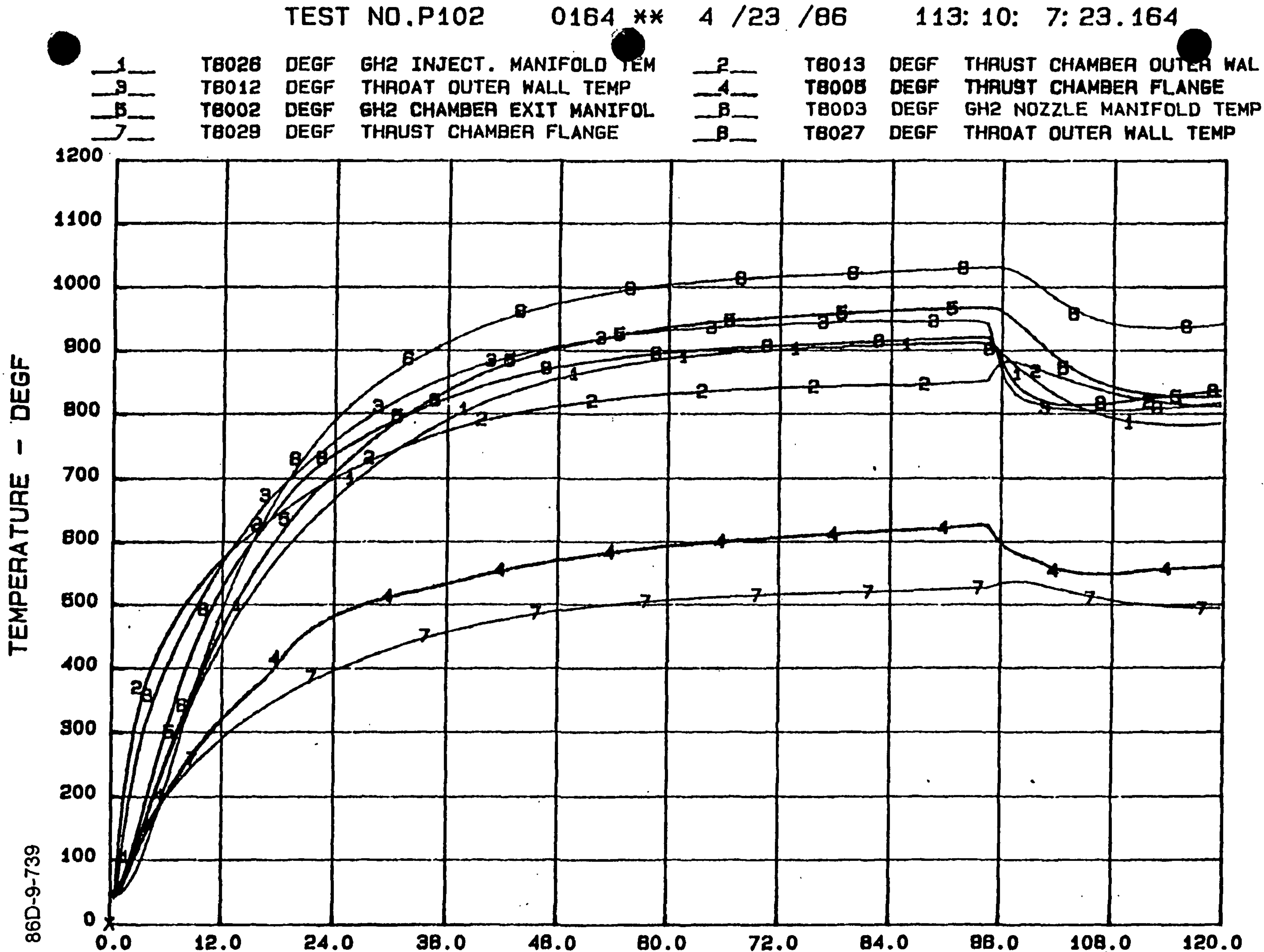

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Figure 40

WORK IN PROGRESS

During the next year, effort will focus on bringing the test bed on line and making it into a tool for demonstrating and developing major propulsion system components. This effort will be directed primarily at oxygen/hydrogen thrusters (from Rocketdyne, Aerojet and Bell) and electrolysis units (from Boeing/Rocketdyne/Life Systems Inc. and possibly MMC/Hamilton-Standard or Hamilton Standard directly). The efforts involved in incoporating the thrusters is expected to involve modification of fluid and instrumentation interfaces and resetting of operating envelopes and redlines. As part of this effort, the regulators on the test bed will be replaced by flight type pressure control valves.

The integration of the water electrolysis unit modules is expected to involve design of flow schematics and physical layouts, and fabrication/procurement of a support structure to hold the modules on top of the test bed, lines, valves connectors, cabling and instrumentation. In addition, effort will be required to establish operating conditions and redlines for the computer controller and initial test sequencing will be prepared. Test plans and updates to drawings and specifications.

FUNDING

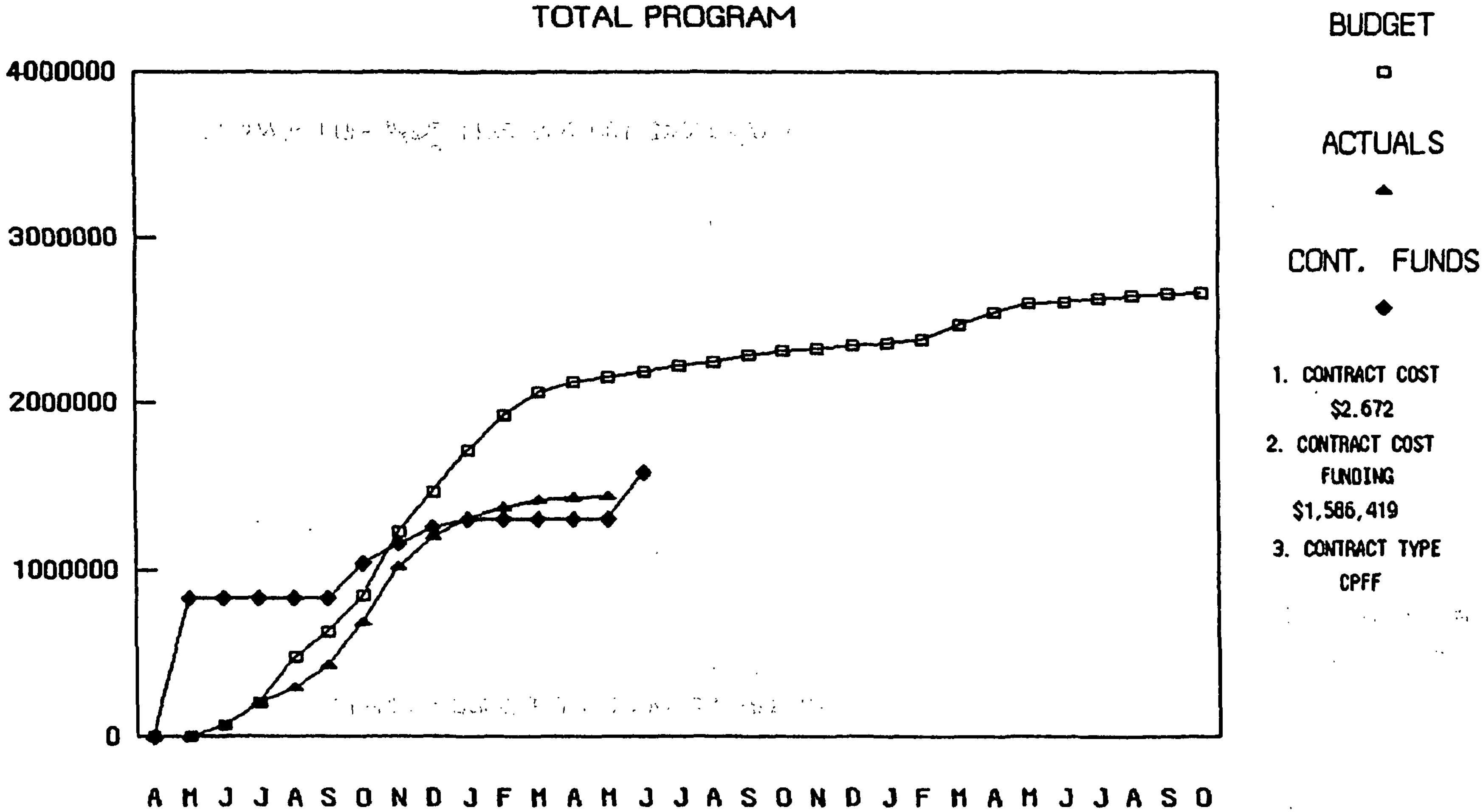
The funding status for the year is shown in Fig 41. As indicated, the actual expenditures are considerably below the original plan because of the incremental approach to funding and the hiatus in funding from January to June.

Figure 41

SPACE STATION PROPULSION

TEST BED

TOTAL PROGRAM



COST BUDGET $2,672,349

ACTUALS W/O CMT $1,435,334

ACTUALS W/CMT $1,436,969

Figure 41